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Aircraft design and test planning with unpredictable dynamic derivative values

Susan J. DeGuzman

To the Graduate Council:

I am submitting herewith a thesis written by Susan J. DeGuzman entitled "Aircraft design and test planning with unpredictable dynamic derivative values." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Bob Richards, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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and recommend its acceptance:

Dr. Solies

Dr. Coleman

Accepted for the Council:

Vice Provost and Dean of Graduate Studies

AIRCRAFT DESIGN AND TEST PLANNING WITH UNPREDICTABLE DYNAMIC DERIVATIVE VALUES

A Thesis

Presented for the

Master of Science

Degree

University of Tennessee, Knoxville

Susan J. DeGuzman
May 2003

DEDICATION

This thesis is dedicated to my son, Joshua DeGuzman, who endured countless hours of rough-housing with his father, Armando DeGuzman, while mom worked behind the computer, and to my husband who made this possible.

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I would like to thank Mr. Robert J. Hanley of the NAVAIR (Naval Air Systems Command) Airworthiness Office. His efforts made this project possible in so many ways including: endorsing the US Navy Test Pilot School (USNTPS) curriculum, funding the research into this topic as well as the time to pursue this project to completion. His leadership and quest for continuous education provided me the knowledge, skills, and abilities to pursue and complete this most important project.

I would also like to thank Dr. Bob Richards formerly of USNTPS for his dedication and continuous efforts to support and provide aviation professionals the opportunity to further their education at the University of Tennessee Space Institute (UTSI) program. He makes it possible for many USNTPS graduates to pursue a Masters Degree.

PREFACE

This thesis discusses the views and recommendations that are solely the opinion of the author and are not official government views or policies. The F/A-18E/F flight simulation testing conducted in this report utilized a Naval Air Systems Command flight simulator that was made available to the author for research efforts. Additional F/A-18 data presented in this report was obtained from several government contracts with the following companies: McDonnell Douglas Aerospace, Boeing, and Bihrle Applied Research.

ABSTRACT

Modern aircraft are designed based largely on the results from wind tunnel tests and flight simulations conducted prior to the start of construction. Predicted aircraft characteristics from wind tunnel tests are used in several aspects of aircraft design and often determine critical design criteria. Utilizing these advanced aircraft design methods has proven to significantly reduce the overall aircraft design cost and flight testing efforts. Over the last 50 years major advancements have been achieved in flight predictions, and we depend more and more on the test results. In general, this dependency has proven to be warranted in many aspects. However, there are areas requiring further research before they are to be depended upon completely. One specific area demanding technological breakthrough is that of improving dynamic derivatives predictions at high angles of attack. These derivatives are presently found through various model tests whose values vary so significantly from one another that it is next to impossible to predict dynamic derivative values with any accuracy. When comparing the predicted derivative values to actual flight test results, the predicted values were seen to vary up to 400% from the actual value. These inadequately predicted values are used to define the flight characteristics of the aircraft in regions including high angles of attack, stalls, spins, and spin recovery, and to define flight control laws.

To further examine this issue an evaluation was conducted to determine how unpredictable dynamic derivative values on the US Navy F/A-18E/F could affect the aircraft's spin characteristics. The derived results show the percentage that the actual derivative values may deviate from the predicted values without significantly altering the aircraft's expected flying qualities. The data indicated that known variations in derivative values greatly altered the time elapsed, the altitude lost, and the number of spins occurring before spin recovery. These results were used to determine an acceptable error band between the predicted derivative values and the actual values. While some derivatives displayed minor flight differences with large changes in values, other derivative changes showed extreme differences in spin conditions, including unexpected entry into an unrecoverable spin, within the maximum variation in predicted derivative values. The results conclude that the current methods of obtaining predicted dynamic derivative values generate errors that fail to offer the adequate values required for aircraft design. To solve this problem more research must be conducted to look into better methodology for testing and predicting these derivative values.

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LIST OF ABBREVIATIONS

Abbreviation	Definition	Units
Alphad	Angle of Attack (flight simulation term)	Degrees
Alt	Altitude	Feet
AOA	Angle(s) of Attack	Degrees
ASRM	Automatic Spin Recovery Mode	N/A
BAR	Bihrle Applied Research	N/A
Betad	Angle of Sideslip (flight simulation term)	Degrees
CFD	Computational Fluid Dynamics	N/A
CG	Center of Gravity	N/A
CR	Characteristic Rating	N/A
Clp	Rolling moment due to roll rate $Clp = \partial C_l / \partial (p*b / 2*V_t)$	Non-dimensional
Clr	Rolling moment due to yaw rate $Clr = \partial C_l / \partial (r*b / 2*V_t)$	Non-dimensional
ClΩ	Rolling moment due to rotation rate $Clp*\cos\alpha+Clr*\sin\alpha$	Non-dimensional
Cnp	Yawing moment due to roll rate $Cnp = \partial C_n / \partial (p*b / 2*V_t)$	Non-dimensional
Cnr	Yawing moment due to yaw rate $Cnr = \partial C_n / \partial (r*b / 2*V_t)$	Non-dimensional
CnΩ	Yawing moment due to rotation rate $Cn\Omega=Cnp*\cos\alpha+Cnr*\sin\alpha$	Non-dimensional
deg	Degree(s)	Degrees
F/A-18	US Navy Fighter Attack aircraft model #18	N/A
Ft	Foot/Feet	Feet
I	Moment of Inertia	Slugs/feet^2
KCAS	Knots Calibrated Airspeed	Knots
LaRC	Langley Research Center	N/A
Lbs	Pound(s)	Pounds

LIST OF ABBREVIATIONS (Con't)

Abbreviation	Definition	Units
MDA	McDonnell Douglas Aerospace	N/A
MSRM	Manual Spin Recovery Mode	N/A
NAVAIR	Naval Air Systems Command	N/A
NASA	National Aeronautics and Space Administration	N/A
NATOPS	Naval Air Training and Operating Procedures Standardization	N/A
NAWC	Naval Air Warfare Center	N/A
PC	Personal Computer	N/A
Phid	Roll Angle off from Straight and Level Flight	Degrees
PID	Parameter Identification	N/A
Psid	Yaw Angle off from Straight Flight	Degree
Rbody(d)	Yaw Rate (flight simulation term)	Degrees/second
RCVRY	Recovery	N/A
RPV	Remotely Piloted Vehicle	N/A
S&T	Science and Technology	N/A
Sec	Second(s)	Second
SRM	Spin Recovery Mode	N/A
USNTPS	United States Naval Test Pilot School	N/A
UTSI	University of Tennessee Space Institute	N/A
$\Omega b/2V$	Spin coefficient (+ for clockwise) *Ω = stability axis rotation rate	Non-dimensional
%cbar	Percent of Mean Wing Chord	N/A

CHAPTER 1: INTRODUCTION

Background

Wind tunnels have been in existence since the early 1700s and many major technology advancements have enhanced their benefits to the aviation industry and data reliability. When humans first concentrated on achieving flight they realized that there was a need to understand the flow of air over aircraft surfaces. This meant building laboratories where wings, fuselages, and control surfaces could be tested in controlled conditions and resultant forces and pressures could be used to improve aircraft design. The first reliable airflow testing method came about in the early 1700s and was called a whirling arm, which was simply a long pole on a rotating shaft spun by a motor. Many problems were encountered with these tests including a large amount of turbulence generated by the rotating arm, and difficulty of mounting instruments and measuring small forces on test models while it was rapidly spinning (reference 3). The first actual wind tunnel is credited to Frank H. Wenham in 1871. It was comprised of a fan with a steam driven engine that propelled air down a 12 ft tube to the aircraft model (reference 4). The Wright brothers took this technology further by mounting a two element balance in the airstream showing lift and drag forces. To this day the heart of any successful wind tunnel test is the balance system that measures the aerodynamic forces acting on the model. Today's technology allows these measurements to be taken by placing highly sensitive strain gauges and accelerometers on the aircraft models.

Wind tunnel test data help engineers eliminate possible problems in aircraft designs prior to construction and establish the expected performance limitations of the aircraft.

The tunnel test results are often used to determine what materials and shapes will be used for wings, fuselages, control surfaces, landing gear, and even propulsion systems (reference 5). Today no military or commercial aircraft is built until it has been thoroughly wind tunnel tested. Currently, wind tunnels are sophisticated in design for 'specialty testing' including: those just for airfoil shapes, propulsion systems, and varying wind speeds (subsonic, transonic, supersonic, or hypersonic). There are also wind tunnel types designed to specifically measure dynamic derivative values during dynamic flight motions, these including: rotary balance, free flight, and forced oscillation type tunnels. Tunnels vary significantly in size and their ability to properly simulate full-scale flight conditions by adjusting the pressure and/or temperature in the test cell. Further technological advancements in wind tunnel designs are still occurring every year, current ideas in work include: laser Doppler velocimetry (making it possible to determine velocities more precisely with light beams), and 'smart walls' which expand and contract in ingenious ways to remove the distorting affects walls have on the tunnel's airflow (reference 5).

Dynamic wind tunnel tests are performed primarily to calculate dynamic derivatives to evaluate the flight characteristics of the aircraft during planned flight profiles and to evaluate structural loads imposed on the aircraft from the forces and moments generated during the tests. Additionally, dynamic wind tunnel data results are often used to validate and verify a relatively new method of obtaining aerodynamic coefficients called computational fluid dynamics (CFD), which is a mathematical method of generating the same data using computers. While dynamic wind tunnel testing has proven to be an extremely useful tool, there are several issues that remain to be fully resolved. First, the models used in these types of wind tunnel test have to undergo high frequency and amplitude motions and must be as lightweight and stiff as possible to reduce induced airflow disturbance and aeroelastic effects. While these effects may never be eliminated, there are new materials constantly being developed which have potential for providing more suitable wind tunnel models. Additionally, dynamic tunnel tests often have problems testing at the natural frequency of the oscillating system and may not be able to collect useful data in this region (reference 6).

The raw data as collected during dynamic wind tunnel tests does not produce useful results without a method of combining these results and depicting their effect on the aircraft's flight characteristics. Flight simulators are the primary method of evaluating the data, using mathematical correlations between the variables to combine them into virtual flight characteristics. Methods of implementing dynamic test data have been the topic of many studies, several examples are given in references 7-10 that include: spin prediction techniques, high AOA stability characteristics, the aerodynamic control characteristics in aircraft dynamics, and model of nonplanar aircraft dynamics. The dynamic derivatives discussed in this report are defined in table 1 and are values commonly extracted from wind tunnel data and implemented into flight simulation mathematical models.

Most every flight simulator in existence has a unique method of implementing these data be it a different mathematical model or unique way to use or look up the data to create simulated flight. Dynamic data is often very non-linear and can be time dependant, meaning that the future value depends on the previous or current value. Validation of the various implementation methods are random and uncontrolled, thus there is no defined industry-wide consensus on the topic. Additionally some simulation developers favor data

Table 1
Dynamic Derivative Definitions

Derivative	Definition
Clp	Rolling moment due to roll rate
Clr	Rolling moment due to yaw rate
ClΩ	Rolling moment due to rotation rate
Cnp	Yawing moment due to roll rate
Cnr	Yawing moment due to yaw rate
CnΩ	Yawing moment due to rotation rate
Ωb/2V	Spin coefficient (+ for clockwise) *

*Spin coefficient is not a dynamic derivative

from specific wind tunnels, claiming that results from other sources are suspect due to facility induced effects. Obviously, these varying methods of data implementation affect the predictive capabilities of the flight simulator model they generate. To evaluate this problem a separate study has emerged called parameter identification or PID. PID is the process of using time histories from actual flight test results and 'reverse engineering' the data to compare the values with those in the flight simulator. Flight rates and moments of inertia are used to calculate the rolling, yawing, and pitching moment coefficients. This method of evaluation has been used for over 15 years to verify and validate many flight simulation models (reference 11).

It is impractical to test all possible flight maneuvers in a wind tunnel, including all possible flight rates, amplitudes, and orientations. Small subsets of these combinations are normally tested and the results are extrapolated to estimate the behavior in untested regions. Most major aircraft platforms are subject to forced oscillation wind tunnel testing in pitch, roll, and yaw to obtain direct damping derivatives, and rotary balance testing to investigate spin damping.

Dynamic stability is defined as the tendency of the amplitudes of the perturbed motion of an airplane to decrease to zero or a new steady state value at some time after the cause of a disturbance has been stopped (reference 1). As a general rule, aircraft must have some form of dynamic stability, although many modern aircraft induce these stabilities through the use of flight control systems which automatically deflect any needed aircraft surface to stabilize the aircraft. The equations of motion for these responses are defined in reference 1 (page 307), and show that each equation is of the second order. Further, when these equations are broken down to be defined as the 'dynamic derivatives', it can be seen that these variables are non-dimensional aerodynamic coefficients. The dynamic derivatives discussed in this text are defined in table 1. Further definitions are provided here to expound on the derivatives discussed in this report and give an overall sense of what they mean in terms of aircraft motions and the effect of the derivative values on the aircraft's responses.

Clp is defined as the rolling moment coefficient due to roll rate, or the roll rate damping coefficient (roll damping). An aircraft is considered to have a stable value of Clp when its value is negative. Clr is defined as the rolling moment coefficient due to yaw rate, and is considered stable when its value is positive. Cnp is defined as the yawing moment coefficient due to roll rate and is considered stable when its value is negative. Cnr is defined as the yawing moment coefficient due to yaw rate, or the yaw rate damping coefficient (yaw damping). An aircraft is considered to have a stable value of Cnr when its value is negative. All of these coefficients are non-dimensional, and their equations are presented in the list of abbreviations, as taken from reference 2. The values of these derivatives greatly affect the lateral and directional flight characteristics of the aircraft including the roll mode time constant, steady state roll rate, spiral mode, Dutch roll mode, and adverse/proverse yaw. These coefficients are further explained in reference 2 (pages 33-9 and 37-6) and reference 12 (pages 417-435).

$Cl\Omega$ and $Cn\Omega$ are calculated terms defined as follows, where α is the AOA of the aircraft: $Cl\Omega = Clp*\cos\alpha + Clr*\sin\alpha$, $Cn\Omega = Cnp*\cos\alpha + Cnr*\sin\alpha$. These terms are derived from rotary balance wind tunnel data, where Ω terms define rotation about the stability axis (where the aircraft's x axis is into the relative wind) and p/r terms define rotation about the body axis (where the aircraft's x axis is aligned with a fuselage reference). $Cl\Omega$ and $Cn\Omega$ are not direct dynamic derivatives but their values are used in the F/A-18 flight simulation to predict spin characteristics and therefore it is equally important that these derivatives are accurately defined. Since these derivatives are calculations based on the addition of the roll and yaw derivative components their results and errors will be summations of the results and errors of the other derivatives (references 13 and 14).

The US Navy F/A-18 fighter/attack aircraft is an excellent representation of the uses, benefits, and short falls of dynamic wind tunnel testing. This aircraft was originally designed in the late 1960s and early 1970s. The first version of the aircraft was the F/A-18A/B with the 'A' model being a single seat aircraft and the 'B' model a two seat aircraft. Upgrades were made to the aircraft in the 1980s and subsequent models titled F/A-18C/D were created. Further advancements made in the 1990s increased the range and payload in the latest generation version the F/A-18E/F. F/A-18 variants all underwent extensive wind tunnel testing to determine dynamic derivative values. All variants of this aircraft are currently in operational use and wind tunnel test data as well as flight simulations are still available for evaluating the effects dynamic derivatives have on the design and test planning of the aircraft.

Bihrle Applied Research (BAR) is a government contractor which has worked with the Navy flight dynamics department for over a decade. The company was contracted to evaluate the issue of unpredictable dynamic data being entered into the flight simulation models. They conducted an evaluation in 1995 to determine the accuracy of several data implementation methods and the use of individual wind tunnel data sets. In this evaluation two separate charts were formed. In the first chart various F/A-18C/D predicted dynamic derivative values were plotted against the actual derivative values received through flight testing, thus using PID to verify the simulation database. In the second chart various F/A-18E/F predicted dynamic derivative values were plotted, however no PID data was available for comparison at that time. The results are provided in figures 1-3 displaying each dynamic derivative as a function of AOA. Each figure displays several test results as further explained in the following paragraphs.

The MDA (McDonnell Douglas Aerospace) database, shown in figures 1-3, is the flight simulation model that was used by the company designing the aircraft to evaluate predicted aircraft responses and were used to make alterations to aircraft design and test plans prior to aircraft production. The conclusions drawn from these plots included the fact that in the majority of the tests the error band is greatest between 20° and 70° AOA and that certain dynamic derivatives are predicted with smaller error bands than others. The error band is defined as the difference between the wind tunnel test results and the flight simulation database. As depicted in these figures the MDA database does not correlate well with any of the wind tunnel data sets.

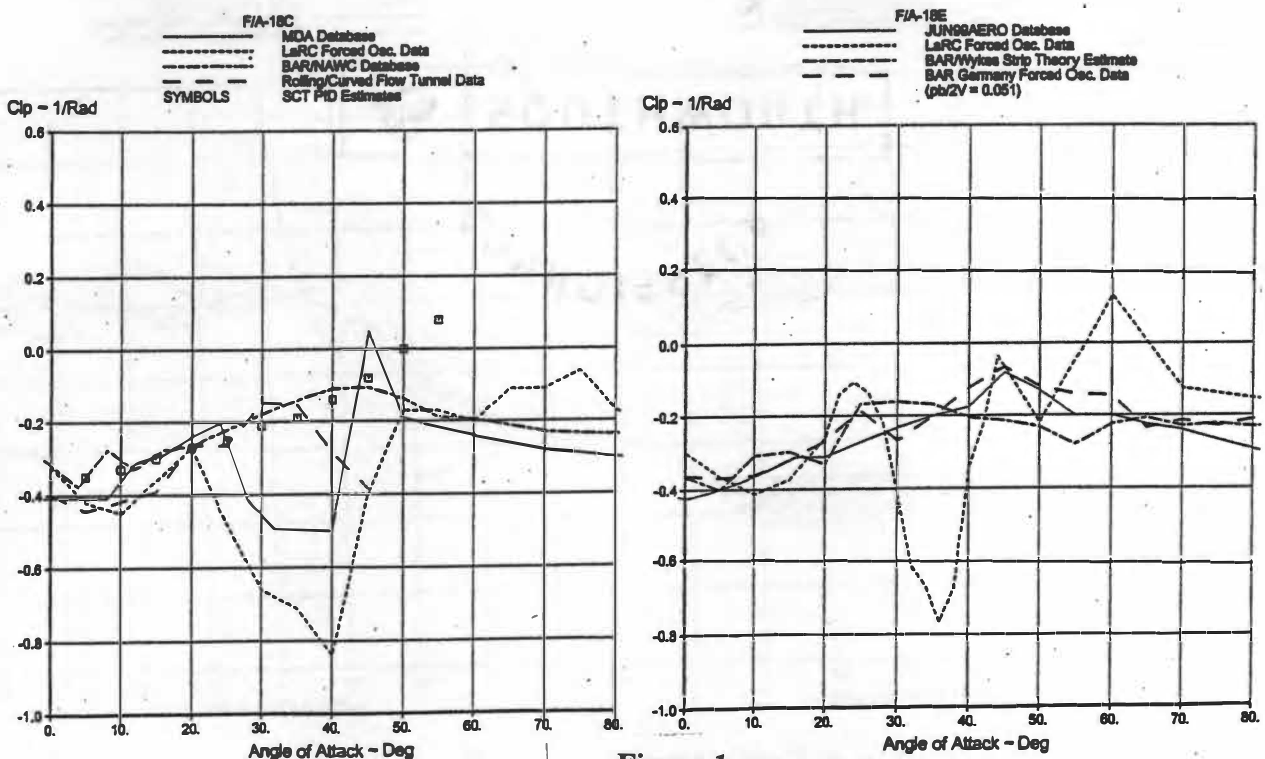

Figure 1

Comparison of Rolling Moment Due to Roll Rate (Clp), F/A-18C and F/A-18E wind tunnel data vs. simulation database.

Mach=0.1, β=0 deg, δLE=34 deg

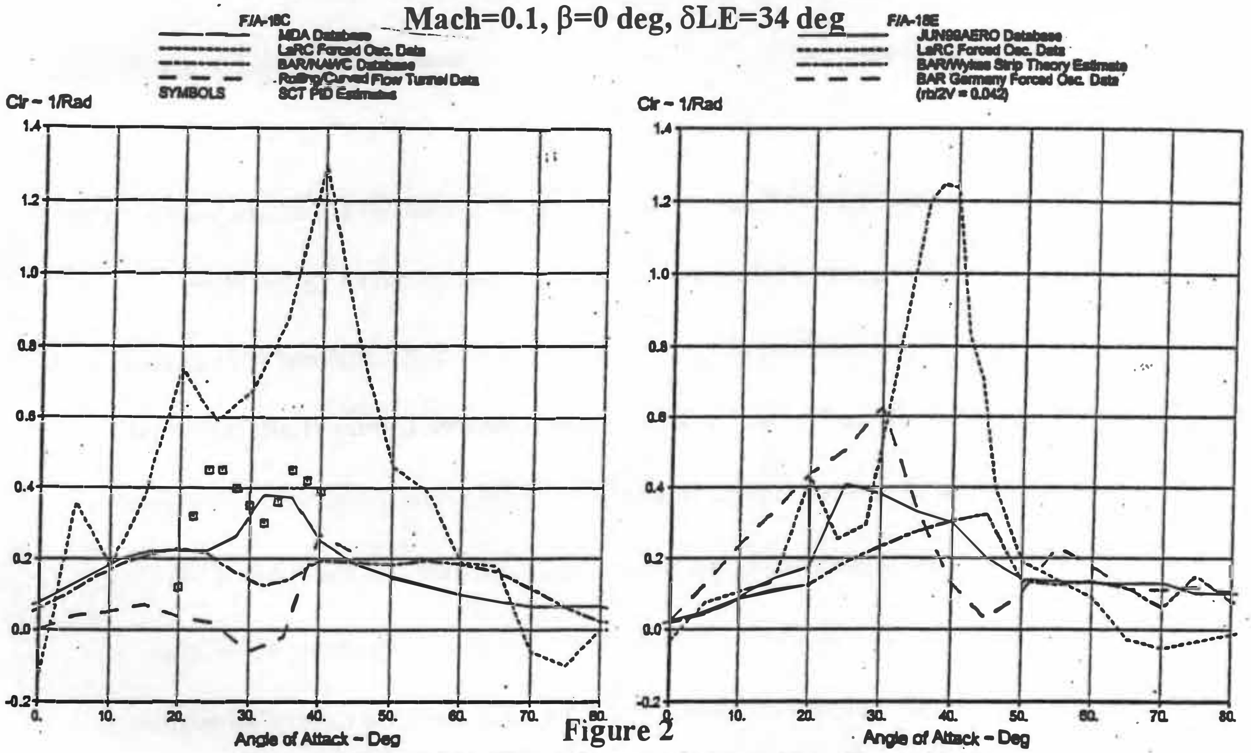

Figure 2

Comparison of Rolling Moment Due to Yaw Rate (Clr), F/A-18C and F/A-18E wind tunnel data vs. simulation database.

Mach=0.1, β=0 deg, δLE=34 deg

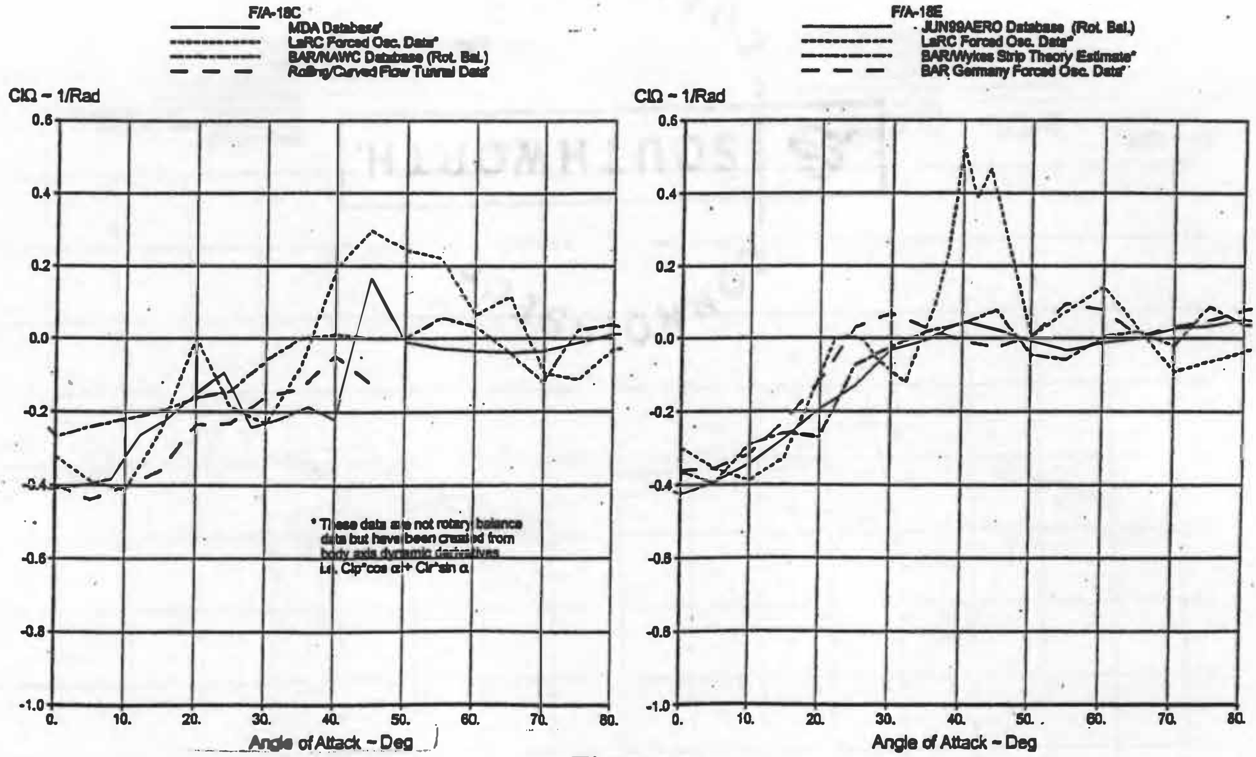

Figure 3
Comparison of Rolling Moment Due to Rotation Rate (ClΩ), F/A-18C and F/A-18E wind tunnel data vs. simulation database. Mach=0.1, β=0 deg, δLE=34 deg, Ωb/2V=0.05

These data sets were used extensively for this evaluation, and are the basis for conducting this research.

The data sets depicted in figures 1-3 are defined as follows for the F/A-18C. The MDA database is the final simulation database as delivered by MDA to the Navy. Numerous updates to this database were incorporated post flight test and PID analysis. The second data set displayed is the NASA Langley Research Center (LaRC) Forced Oscillation data from their wind tunnel; this facility is often considered one of the best sources of dynamic derivative data in the USA. The third data set, the BAR/NAWC (Naval Air Warfare Center) database, was constructed by the Navy using BAR as a contractor, as a separate database from that of MDA with alternate uses of all available wind tunnel data. The BAR/NAWC database incorporates data from the BAR Rotary

Balance and Forced Oscillation wind tunnels in Germany, which were not accepted by MDA. The fourth data set displayed is the Rolling/Curved Flow Tunnel data from a wind tunnel at Virginia Polytechnic Institute and State University. This tunnel simulates the motion of the aircraft in curved or rolling flight, by actually curving or rolling the airstream as it passes over the model while it also provides the proper velocity distribution. More information on this tunnel is provided in reference 15. These charts also depict several PID data points to compare actual flight test results to predicted and simulated databases.

The data sets depicted in figures 1-3 are defined as follows for the F/A-18E. The JUNE99AERO database was developed by Boeing (McDonnell Douglas Aerospace merged with Boeing in 1997. For the purpose of this report all work done prior to the merger is attributed to McDonnell Douglas Aerospace, and all work after that date is attributed to Boeing) and used for aircraft design and flight test planning. By this date Boeing was incorporating BAR's wind tunnel data with all other data available. The second data set is again the LaRC Forced Oscillation data, and is from the same wind tunnel the F/A-18C used above. The third data set displayed is BAR/Wykes Strip Theory Estimate, utilizing a complex mathematical technique for reducing wind tunnel data from BAR's Rotary Balance wind tunnel. Many organizations use varying strip theories, in which pressure distributions along streamwise strips are used as input to two dimensional boundary layer calculations (reference 16). And finally, the BAR Germany Forced Oscillation data is from a BAR wind tunnel.

At first glance one could say that the MDA database for both the F/A-18C and F/A-18E were largely derived as an average of all data presented on these curves, but upon closer examination the trend and actual calculations prove otherwise. Additionally, averaging such a wide range of data does not seem to be the most scientific method of establishing a 'proven' database. To further evaluate the background on this subject we will look into the depth of this issue as it occurred in the early F/A-18 models since the testing of these models is well documented and available.

Initial flight results of the F/A-18A in 1979 indicated that the cruise performance was significantly below expectations, with a deficit of about 12% in cruise range. This meant the aircraft could not travel as far on one tank of gas as was expected, thus reducing its overall effectiveness as a military fighter/attack aircraft. Many reasons were identified for this poor performance including inadequate aerodynamic efficiency due to poor flight control computer scheduling of leading edge and trailing edge flaps (reference 17). Additionally, aerodynamic drag was significantly higher then had been predicted in wind tunnel tests. Several major modifications were incorporated to the aircraft after these issues were realized which cost the government millions of dollars. Cost overruns might have been avoided if the wind tunnel data had more accurately defined the issues prior to aircraft construction. For the purpose of this report the term accuracy is defined as freedom from error where actual aircraft data is the truth measure. Post-construction modifications included: increasing the wing leading edge flap radius, designing variations in the leading edge extension camber, and filling in the slots in the leading edge extension and fuselage junction. These problems all relate to inadequate static wind tunnel data which is a major issue. We can not expect to adequately define the dynamic derivatives if the static data on which they are based is incorrect. The adequacy of static wind tunnel data could be the basis of a separate study which would provide helpful insight to this evaluation of dynamic data.

In 1979 the F/A-18A suddenly and unexpectedly departed from controlled flight at a flight condition that was thoroughly evaluated in wind tunnel tests. None of the wind tunnel data predicted this characteristic. After this event, the F/A-18 was put into NASA's full scale wind tunnel and this flight region was re-evaluated. Upon further review, engineers found they could eliminate this problem by increasing the deflection of the leading edge flaps from 25 deg to 34 deg at high AOA. Fortunately this was simple, but one would hope that all of the wind tunnel testing conducted prior to flight test would have found this problem. The use of wind tunnels is supposed to mitigate the risks of encountering unexpected out of control flight which obviously was not the case in this event.

All versions of the F/A-18 were developed with a computerized flight control system that adjusted the aircraft's control surfaces to produce the desired output for the pilot's input. With the flight control system activated, the F/A-18, even in the earliest version, was extremely resistant to spins (prospin controls had to be held for over 20 seconds to induce a spin). This was evident during many wind tunnel tests prior to construction. However, another phenomenon called 'falling leaf' was found in flight test which had not been predicted in the wind tunnel tests. A falling leaf was encountered by stalling the aircraft and forcing a series of incipient spins to the left and right causing the aircraft to fall like a leaf from altitude. In the early 1980s this unintentional maneuver was categorized as a severe out of control flight problem during developmental tests of the F/A-18A (reference 17). Flight testing failed to find a solution for this problem prompting the establishing of the aft center of gravity limit and the maneuvering limit for the aircraft. During the early 1990s numerous F/A-18A-D aircraft were lost due to unintentional falling leaf entries that were unrecoverable. The F/A-18E/F was still in development at this point and thus was exhaustively tested in wind tunnels and in flight for falling leaf susceptibility. It was found that the 'unaugmented' aircraft did exhibit the falling leaf mode, but the new computerized flight control system suppressed the onset of this mode and the problem was considered solved. The F/A-18E/F continued extensive wind tunnel, flight simulation, and flight test efforts, and over the course of three years totaled 221 flights devoted solely to high AOA maneuvering, departure resistance, and spin testing (reference 18). These efforts proved successful in improving the departure resistance from that of the earlier F/A-18 aircraft. The Navy is now testing a new flight control system to eliminate spin problems in the earlier model F/A-18 aircraft.

Flight testing is currently underway at Naval Air Station Patuxent River in Maryland to evaluate the updated flight control laws that will reduce the occurrence of out of control flight in the F/A-18A-D. Using engineer simulators, it has recently been determined that adjusting the recovery techniques used may assist in recovering an aircraft that was thought to be unrecoverable. However, it is difficult to prove this in flight because the maneuvers are almost impossible to duplicate in a controlled fashion such that they can be compared and evaluated. Additionally, NAVAIR and Boeing have modified the flight control computer to improve resistance to and recovery from out of control flight. This new flight control system was designed with the new architecture being used by the F/A-18E/F. Additionally, flight testing will evaluate these new flight control laws with three major changes to the existing control system: feedback of sideslip and sideslip rate to differential ailerons and stabilators, roll axis gain scheduling above 35 deg AOA, and the use of opposite differential stabilator to improve roll coordination above 35 deg AOA (reference 19). All three of these items could have been realized and fixed prior to the first F/A-18 flight if the dynamic derivative wind tunnel data had accurately depicted the issues. With the tests not yet completed we can only anticipate that these changes will improve the flight characteristics of the aircraft, and simply prove that better prediction of dynamic derivatives will significantly reduce the life cycle cost and mitigate the risks of flying with unpredictable dynamic derivative values.

Purpose

An evaluation was performed using a NAVAIR F/A-18E/F engineering flight simulator to examine the aircraft's response when subjected to spin conditions with various dynamic derivatives values. The results demonstrate the percentage that the actual dynamic derivative values may deviate from the predicted values without altering the aircraft's spin characteristics. The purpose of this evaluation was to estimate how accurate predictive methods must be to prove more beneficial for use in aircraft design and test planning.

There are currently several methods of predicting aerodynamic coefficients and their results vary significantly from one another and from the actual flight results. The predicted dynamic derivative values are used for aircraft design and test planning and form the MDA flight simulation database. This database itself has been found to vary considerably from the various predicted values and the actual flight results received from PID analysis. Although several meetings and discussions on the subject were held between MDA and NAVAIR engineers, no definition was provided to declare which prediction data was used in forming the MDA database. This test was conducted to examine the effects the MDA database would have on aircraft design and flight testing if the dynamic derivative values used to create it were inaccurate.

Description of Test Equipment

To conduct this evaluation the engineering flight simulation workstation shown in figure 4 was used. In support of the F/A-18E/F aircraft development NAVAIR required an engineering simulator to review and analyze flight data and perform flight simulation evaluations independent from the company building the aircraft (Boeing). Bihrle Applied Research Inc. was hired to fulfill this requirement with their D-Six simulation environment. D-Six is PC (personal computer) based and combines a graphical interface, analysis tools, and the computational power needed to run complex simulations at real time (reference 20). The simulation utilizes the most recent software advances, efficiencies, and graphic

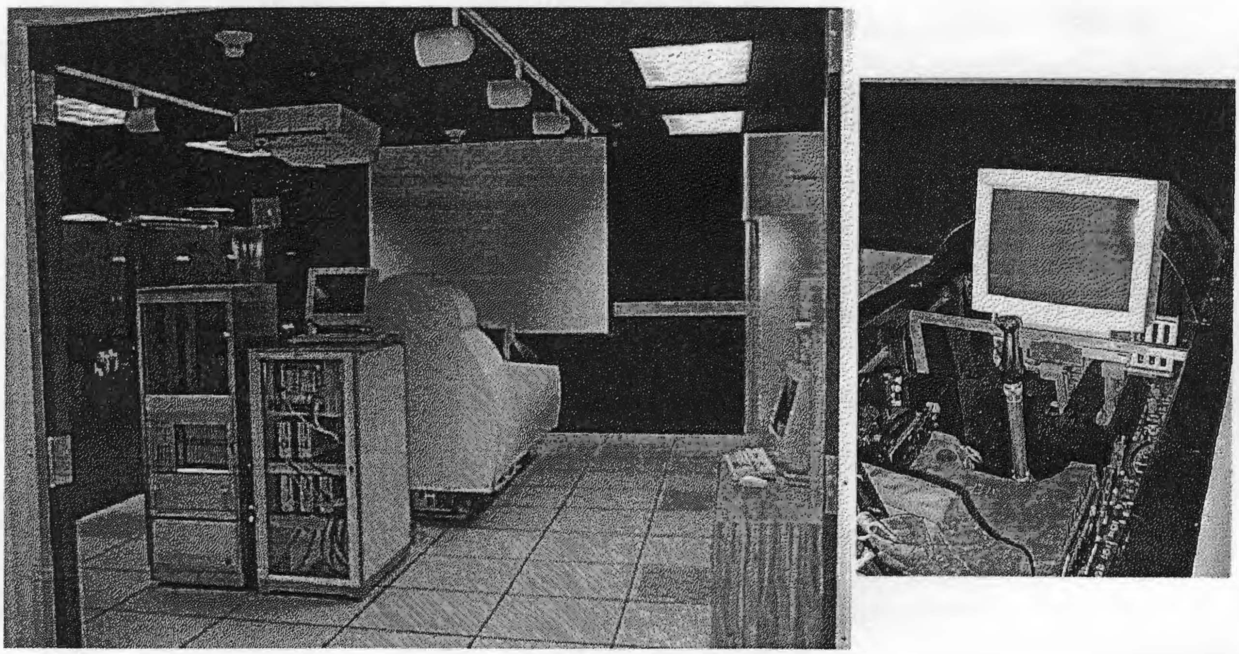

Figure 4
Flight Simulation Workstation

capabilities available on a PC running Windows. It can easily communicate with plug in hardware such as control sticks, rudder pedals, and throttle quadrants. This evaluation was run using the D-Six software in a full cockpit non-motion mock up of the F/A-18E/F, equipped with a calibrated control stick, rudder pedals, a throttle quadrant, a mock instrument panel, and cockpit seat similar to that of an F/A-18.

This high fidelity engineering simulator used the same aerodynamic database as Boeing used for aircraft design planning and development of flight control laws. The simulation database consisted of multi-dimensional aerodynamic tables, to include: math models of the propulsion system, flight control system, and hinge moment characteristics. The tables were manipulated to create the flight characteristics of the aircraft via table lookup algorithms. The entire flight model consisted of more then 1.7 million data points with more than 4,700 variables and over 30,000 lines of FORTRAN code. The data tables were converted from Boeing's CTAB format via AeroPort to be integrated into the D-Six software (CTAB and AeroPort are Boeing flight simulation software systems). Original Boeing FORTRAN flight control codes were recompiled and directly added to the D-Six simulation.

The D-Six engineering simulator was used to support many revisions to the aerodynamic model and changes to the flight control laws during the years 1996 to 2000. Many of these updates were initiated to 'reverse engineer' by using known flight data and implementing it into the flight simulation database through PID analysis. For the purpose of this evaluation the original aerodynamic database was used, prior to any PID updates, because this evaluation is partly trying to determine the accuracy of the wind tunnel data prior to being modified with PID analysis. If an updated version of the aerodynamic database was used it would not generate an accurate depiction of the inadequacy of current dynamic derivative values as generated in current wind tunnel tests. Therefore, during this evaluation the D-Six simulator was loaded with 'May 96 Aero data' supplied by McDonnell Douglas Aerospace.

Scope of Test

The F/A-18E/F flight simulator has a staggering 4,700 variables. Many of these variables are derived from wind tunnel tests, while others are calculated or designed into the aircraft (such as flap deflections or wing thickness). For obvious reasons it is not feasible for one evaluation to analyze all 4,700 variables. Wind tunnel results tend to be reasonably accurate when measuring static data and even dynamic data between zero and twenty deg AOA. Therefore, the scope of this test was limited to dynamic derivatives at high AOA. The region of flight that is most affected by dynamic derivative values at high angles of attack (AOA) is that of out of control flight or spin conditions, because these derivatives define complex motions in several axes which are most pronounced in these high rate flight regions.

This report concentrates on the major lateral and directional dynamic derivatives and those derived for flight simulation databases to limit the scope of this research to a reasonable number of data points, therefore only the following six derivatives were considered and tested: Clp, Clr, ClΩ, Cnp, Cnr, and CnΩ. These derivatives define the rolling and yawing moments due to roll rate, yaw rate, and rotation rate. There are several other dynamic derivative values, including many that characterize the longitudinal stability of the aircraft. Lateral and directional motions are extremely dependant on one another and would be difficult to evaluate separately. Figures 1-3 show the difference between wind tunnel data, the flight simulation database values, and PID analysis for the lateral or rolling derivatives (Clp, Clr, and ClΩ). Data of this sort were not available for the directional or yawing derivatives (Cnp, Cnr, and CnΩ). This alone was not a reason to eliminate yawing derivatives from the evaluation. However, an assumption had to be made that the directional dynamic derivative values are also inadequately measured and that their wind tunnel data, flight simulation database, and PID analysis results vary significantly from one another as the rolling dynamic derivatives do. This evaluation will prove beneficial even if these values do not vary as much as the rolling derivatives, as one can be certain that the values do vary slightly. To control this evaluation it was decided to use 'raw' data, meaning the flight simulation database was compiled prior to flight test adjustments. This database was fully developed in May of 1996 and was used extensively in aircraft design and flight test planning. After this date, numerous updates were made to the flight simulation database based on PID analysis and changes to the flight control system based on pilot comments and flight test data. However, the updated databases were not assessed in this evaluation.

Test Conditions

This evaluation was conducted in conditions that were as similar as possible to the actual flight test conditions. The F/A-18E/F was flight tested for spin conditions with many different loadings and initial conditions but the one chosen here was found to be the most common mission configuration. First, the store (or weapon) loading of the aircraft for this evaluation was for the Fighter Escort loading. This loading is commonly used in

Table 2
Fighter Escort Properties

Configuration	Gross Weight (lbs)	CG (%cbar)	Ixx ($slug \cdot ft^2$)	Iyy ($slug \cdot ft^2$)	Izz ($slug \cdot ft^2$)	Ixz ($slug \cdot ft^2$)
Fighter Escort Loading	35,065 (mid fuel)	28.6 (mid fuel)	37,926	178,279	210,000	-2,516

the US Navy fleet for training and actual military missions. A list of weights and inertial moments corresponding to this load configuration are presented in table 2.

In order to control this evaluation all tests were conducted with one flight configuration and one set of initial flight conditions, varying only the underlying dynamic derivative values. This method of testing provides constant inputs to each simulation run so that they may be directly compared. The initial conditions used in this evaluation were also comprised of data similar to the departure testing conducted during the F/A-18E test flights. The initial conditions used during this evaluation are presented in table 3.

The initial conditions in table 3 were saved in the flight simulator and repeated with altered dynamic derivative values. These conditions force the simulation to immediately enter spin conditions with most any dynamic derivative value entered. The spin entered in this case is intentionally quite flat, meaning that there is little longitudinal motion. This condition was selected due to the limited scope of this evaluation for only analyzing lateral and directional dynamic derivatives. Spin conditions were used as a method of comparable testing, however they are just an example of how dynamic derivative values can alter flight conditions. Additional testing could have been done using aggressive maneuvering during controlled flight, however this was not as easily replicated in the flight simulator. The premise for this evaluation is that spin conditions

Table 3
Initial Flight Conditions

Aircraft Configuration		**Flight Conditions**	
CG	28.6% (mid fuel)	Altitude	40,000 ft
Landing Gear	UP	Indicated Airspeed	200 ft/sec (118.5 knots)
Flaps	AUTO	Sideslip Angle	0 deg
Speedbrake	Retracted	Angle Of Attack	70 deg
Throttle Settings	Idle	Yaw Rate*	80 deg/sec

***This initial yaw rate was induced by the simulator through several control deflections, specifically a horizontal stabilator setting of -24 deg, ailerons at +50 deg, rudders deflected -40 deg, and a TEF deflection of +4 deg following the standard sign conventions for aircraft as defined in reference 2 (page 17).**

will adequately demonstrate the effect inaccurate dynamic derivative values have on aircraft flight characteristics.

The F/A-18E/F aircraft flight controls are designed to automatically react to the occurrence of a spin. This reaction is a flight control mode called the automatic spin recovery mode (ASRM). This mode is entered when both of the following conditions are met: airspeed is below 120±15 KCAS and the yaw rate exceeds 15 deg/sec for over 15 seconds or exceeds 50 deg/sec for over 2 seconds. This mode is maintained until the following conditions are met: airspeed exceeds 245 KCAS or the yaw rate drops below the above thresholds (reference 21). There is also a manual spin recovery mode (MSRM) which allows the aircraft to bypass flight control laws and responds directly to pilot inputs, however, in this aircraft the mode results in aircraft departure from controlled flight and prevents spin recovery thus it is prohibited (reference 21). The simulation workstation is designed with the same mode initialization, therefore the majority of these tests are run in ASRM to adequately resemble true spin flight conditions. The F/A-18C/D also has a spin recovery mode (SRM) but it is unique in its characteristics. This SRM is engaged when the following conditions are met: airspeed is below 120±15 KCAS, yaw rate exceeds 15 deg/sec, and the control stick placed in the direction indicated on the pilot's display (reference 22). In this mode the pilot has full authority over the main flight control surfaces, except for leading edge flaps that are driven to 34 deg down and trailing edge flaps to 0 deg. While the F/A-18E/F is incapable of recovering out of control flight with the MSRM engaged, the F/A-18C/D is unlikely to recover from out of control flight without the SRM engaged because the flight control laws prevent the necessary stabilator and aileron deflections at high angles of attack needed for spin recovery in this aircraft model. These aircraft are inherently unstable, specifically the directional stability is so weak that the nose wanders without artificial yaw stability control laws. Additionally, even small amounts of lateral stick can generate excessive yaw making the aircraft very susceptible to nose-slice departures with even small stick deflections.

Method of Test

Testing was conducted using a NAVAIR F/A-18E/F flight simulation workstation, which provided a high fidelity test platform to investigate the effects of inaccurate dynamic derivative values. As previously mentioned, the simulator was loaded with the MDA database version May 96 Aero. This database provided the baseline dynamic derivative values that were used in aircraft design and test planning. For each evaluation a baseline test was conducted using the unaltered MDA database and compared to an altered database test run to compare and contrast the changes in flight characteristics.

Several attempts were made to manually fly the flight simulation into a spin condition using the cockpit controls. It was determined that the evaluation would be more controlled with initial conditions fed into the simulation programming allowing the spin conditions to be generated by the computer. This proved to be a very efficient method of beginning each new test run and allowed for a significant increase in the number of test runs attempted. The flight simulator allows one to easily alter over 600 variables as initial conditions, these include: weapons carried, altitude, airspeed, center of gravity, fuel states, control surface or pedal/stick deflections, AOA, and more. Once the data are entered and the flight simulator is put into run mode, the computer runs extensive calculations and table look ups to automatically provide the simulation pilot with the expected flight characteristics for all given initial conditions.

There are several different testing procedures that may be executed on the F/A-18E/F workstation to receive the required information. Four distinct test plans were considered, each of which would provide useful comparisons and insights for future testing. These methods include: comparing the results with varying spin recovery techniques, alternate methods of varying the dynamic derivative values, alternate initial flight conditions, and the method chosen as discussed below. The testing method chosen for this test focused on a flight initialized in a relatively flat (horizontal) spin with constant initial conditions and recovery procedures and only one dynamic derivative change per run. In this manner it was possible to insure that an identical spin would occur in each test run enabling a controlled evaluation to be conducted in which all results may be compared. After the aircraft had begun rotating it was then allowed to recover by means of a hands free technique. This technique is based on utilizing the F/A-18E's ASRM without pilot control, and also ensures a controlled evaluation.

The flight simulator allows one not only to vary the initial conditions of the flight, but also to directly alter most of the 4,700 variables which make up the simulation database. To conduct this evaluation the dynamic derivative values were directly altered in this manner. Each derivative was flown through the planned flight profile at it's baseline value which was the predicted derivative value used for aircraft design and flight test planning. The derivative values were then altered individually by several multiples, and the flight profile was re-flown and compared to the baseline value's flight results. The flight simulation workstation also contained a graphing capability which was used to plot chosen flight data from each test against the data received when the simulator was run with the baseline values. Once these plots were completed it was possible to determine an acceptable percent difference between predicted and actual dynamic derivative values that would provide the necessary flying qualities for safe flight testing, and therefore would also be acceptable for aircraft design purposes.

Figures 1-3 were used to determine adequate bounds for varying the dynamic derivative values, specifically the proven F/A-18C data. These figures are results from several F/A-18C/D wind tunnel tests, the final flight simulation database, and PID analysis points. Comparing the results from wind tunnel tests to the PID analysis it was obvious that the data may vary significantly, as seen in figure 1 where wind tunnel data demonstrated variations up to 400% (or a multiple of 4) from PID analysis values. Since this was the worst case of variation, it was the largest variation tested in this evaluation, and is considered to be a possible error which could be implemented into a simulation database. In order to ensure that a range of all possible derivative values were tested in this evaluation the following percentages of the predicted derivative values were plotted together and compared for each dynamic derivative:

Plot 1: 100%, 200%, 300%, 400%
Plot 2: 100%, 110%, 125%, 150%
Plot 3: 100%, 90%, 75%, 50%
Plot 4: 100%, 0%, -100%, -200%

All plots contain a test at 100% derivative value which is the result of the unmodified simulation database baseline data being run through the spin profile, and is plotted for comparison purposes.

Each of the derivatives studied was altered by varying percentages (or magnitudes) and the effects of these changes were compared. The F/A-18C/D tests shown on figures 1-3 demonstrate the likelihood and magnitude of errors that are common in today's data prediction methods. From these figures it can be noted that relatively small percent errors (at or below 50%) are common, and larger errors (between 50% and 400%) are likely. In the initial evaluation, as the derivatives were altered significantly, it was seen that changing certain coefficients had more of an effect on the aircraft's flying qualities then did others. The coefficients whose altered effects were significant (within a 50% error region) were tested further. The 50% range was chosen for this evaluation because this percentage error was common in all of the derivative predictions in figures 1-3. The derivatives that displayed extreme changes in flight characteristics during the spin profile were reevaluated further within a 25% error region.

The flight simulation plots, generated with altered dynamic derivative values run through the same spin profile, include the results at 100% of the predicted value providing a constant such that each test may be compared. The first test alters the coefficients from

200% to 400% which gives results in the extreme circumstance that the predictive testing methods provide that measure of inaccuracy. The second test focuses on the results of changes at or below 50%. This amount of error is common throughout most predictions. Finally, the third and fourth tests simply repeat the first two percentages to reduce the predicted value of that coefficient as opposed to increasing the predicted values. This method of altering the dynamic derivative values proved to be effective for examining a large range of values for each derivative.

The dynamic derivative values that were altered (Clp, Clr, ClΩ, Cnp, Cnr, and CnΩ) can all be expressed as functions of the aircraft's AOA, and can be represented in that manner in graphical form. When the derivative values are altered by means of a linear basic multiplier (as is done here) the curve is shifted to higher or lower positions as individual points are increased/decreased by the same value. Past studies revealed that common errors in wind tunnel test data generally do not occur in this fashion. Future tests would benefit from flight simulation workstation that could directly alter the values of each coefficient along the curve to directly represent individual wind tunnel test results. However, that method would not prove to be as controlled and/or comparable as the method used in this test. The limitations to this type of test include that each dynamic derivative value along the curve gets multiplied by the same magnitude and therefore the slope of the curve gets multiplied by that magnitude as well. Although it is not probable to believe that any predicted value could be in error by an exact magnitude across it's values, there are endless tests which could be performed with varying derivative values and it is unlikely that any would prove to perfectly match the errors generated in prediction values.

Data Processing

The flight simulation workstation provided a graphing routine to compare the data from each test. The results were plotted in sets of four runs, each set consisted of one plot of the predicted derivative values (100% of the baseline database value) and three plots in which the chosen derivative(s) had been multiplied by a constant coefficient. This multiple indicates the percent of the predicted value that is being run for that test. In order to compare the results the following variables were plotted verses time of flight for each spin profile flown: AOA, angle of sideslip, altitude, angle of roll, magnetic heading, and yaw rate. These variables provided the needed information to establish a point at which the spin could be considered recovered and important insights to several other spin characteristics that could be compared.

Due to the complexity of dynamic derivatives and their interdependence it was necessary to determine individual sensitivities and the sensitivity of the aircraft's flight characteristics to combined dynamic derivative inaccuracies that would be apparent in frequently performed maneuvers. The test was initiated by altering the coefficients independently and running each data set through the above mentioned procedure. This demonstrates the change in aircraft characteristics that would take place if only one of the derivative values was inaccurate. One test was then conducted with a percent change given to each dynamic derivative. This variation provides a method of testing multiple errors in the predicted derivative values. Further testing could be conducted with a variety of different error combinations, creating endless test possibilities.

The accuracy of the data presented in this report is dependent on the flight simulation providing accurate results and the interpreter's ability to accurately read the results from their graphical format. The flight simulation provides results to the ten thousandths decimal place (ex. 0.0000) and therefore data received from the simulation tests can be no more precise then that value. However, the simulation results are not printed out in value tables but are presented in graphical format to be read by an interpreter. The results for this test were read using a ruler with 1/16th inch increments. Each graph has a different scale and therefore there is no consistent value for data precision in these readings. However, each scale can be broken down to the number of 1/16th inches that can be measured within its scaling. The precision can be no greater then that value. For example, an altitude chart is scaled for 2000 ft increments, the size of this chart only allows 4/16th inch increments to be measured within this scale, therefore the accuracy of altitude readings is no greater then 500 ft (2000 ft divided by 4 increments). Additionally, each dynamic derivative evaluation was limited by the number of tests conducted. For example, Clr was tested at the following percentages: 400%, 300%, 200%, 150%, 125%, 110%, 100%, 90%, 75%, 50%, 0%, -100%, and –200%, therefore no test data is available for this derivative at say 137% of it's simulated value. For the purpose of this test the data is assumed to be linear between test results, but due to the nature of dynamic derivatives this may not always be the case.

CHAPTER 2: RESULTS AND EVALUATION

The flight simulation workstation was flown through the same spin profile with altered dynamic derivative values and its graphing routine was used to generate plots depicting the effect these altered values had on the aircraft's flight characteristics. These plots, provided in the Appendix, displayed the following variable readouts for each spin profile: AOA, angle of sideslip, altitude, angle of roll, magnetic heading, and yaw rate. The values in these plots were used to compare the altered flight characteristics. The plots provided the information needed to determine the number of spins occurring, the time elapsed during the spin, and the altitude lost before the aircraft was recovered. These values were extrapolated directly from the plots and their results, shown in tabular format for comparisons in tables 5-10. This section will refer mainly to the tabular results, which can be checked against the plots in the Appendix for reference.

The plots generated by the flight simulation database are provided in the Appendix. Due to limited plotting capabilities in the simulator, desired formatting was not possible. The parameters plotted are defined as:

Time = time (sec)
Alphad = AOA (deg)
Betad = angle of sideslip (deg)
Alt = altitude (ft)
Phid = roll angle off from straight and level (deg)
Psid = yaw angle off from straight flight (deg)
Rbodyd = yaw rate (deg/sec)

The plots that were received from each evaluation were compared against each other in order to obtain meaningful results. The main concern of this analysis was to examine the differences in the aircraft's spin recovery characteristics. All plots are based on the time axis for comparison purposes with plots having a reference run at 100% derivative values (with no alteration to any coefficients). In order to compare the recovery times from each analysis, full recovery was assumed when the yaw rate crossed zero. Across all tests it was found that this was a good indication of spin recovery. Zero yaw rate is indicated by the time history line crossing the horizontal axis in the graph that is labeled Rbody, which is the flight simulator's term for yaw rate. Each of these test runs was allowed to persist for 45 seconds and its recovery time was indicated as the time when the yaw rate crossed the horizontal axis (0 yaw rate). Once the recovery time was established, it was possible to determine the altitude lost in recovery by cross checking the recovery time with its corresponding response on the altitude chart. It was also possible to determine the number of spins that occurred before recovery by counting the number of times the aircraft heading rotated a full 360 deg which is indicated as Psid on the plot printouts. The remaining charts were used primarily to examine the overall damping characteristics of the spin in AOA, sideslip, and roll angle.

The charts are further divided into individual run numbers. Each flight simulation test that was conducted with a given variation in dynamic derivative values was given its own run number and those runs were then plotted together for comparison purposes. Each run is defined by the amount a derivative value was altered and is listed at the bottom of each chart. An example of such a located in Appendix figure A1a: %(clp,clr,clo)= (100,100,100) (200,100,100) (300,100,100) (400,100,100), this indicates that the run numbers on this figure (runs 1, 5, 6, and 7) have respective dynamic derivative values of the following.

Run 1: clp=100%, clr=100%, clo=100%, or (100, 100, 100)
Run 5: clp=200%, clr=100%, clo=100%, or (200, 100, 100)
Run 6: clp=300%, clr=100%, clo=100%, or (300, 100, 100)
Run 7: clp=400%, clr=100%, clo=100%, or (400, 100, 100)

The tabular results were arranged in a manner such that quick comparisons could be made between various percentages (multiples) of a specific derivative and between the individual altered derivatives themselves. For each derivative the results are listed by the percentage it is altered from the predicted value. The results indicate the number of spins occurring, the amount of time elapsed, and the altitude lost before the aircraft recovered from the spin. Each test also lists a short comment about the appearance of the flight and its time history plot shown in the Appendix. These comments alone can't fully explain the appearance of each time history, therefore the Appendix plots should be reviewed if a better description is desired. The comments made for each flight were chosen from a list of eight possibilities described in table 4. Each general characteristic/comment was given a number called the characteristic rating (CR) which can also be used as a quick comparison between tests.

In actual flight tests the most important spin characteristics are the amount of time needed to recover and the altitude lost during that period. These flight test values are consequential because the pilot's response is critical for the safe recovery of the aircraft.

Table 4
Definitions for Characteristic Rating

CR	Comment	General Description
0	Reference	Flight at 100% off predicted value
1	Unnoticeable differences	shows no differences from reference flight
2	slight differences	recovery within 0-1sec of reference, slight differences
3	small differences	recovery within 0-1sec of reference, small differences
4	noticeable differences	recovery within 1-2sec of reference recovery
5	fast damping	recovery within 2-5sec of reference recovery *
6	slow damping	recovery time 5+sec after reference recovery
7	very slow damping	slight signs of recovery
8	no sign of recovery	no sign of recovery

* minor exceptions are made in cases where time does not seem a good defining factor for overall spin characteristics

Pilots have been trained to initiate a recovery method that will recover the aircraft in an allotted time period. When this time is significantly surpassed, the pilot may deploy the spin parachute (if available) or even eject from the aircraft for fear of a non recoverable spin. The reason that this test is only run for 45 seconds is simply because a pilot would generally alter the recovery mode if the aircraft displayed no sign of recovery by that point. The results from each test are shown in tables 5-10 with an analysis of those results in the following paragraphs.

Table 5 depicts the results of the flight simulation workstation test when altered values (percentages) of Clp (rolling moment due to roll) were flown through the spin profile. The graphical results from these tests are presented in Appendix figures A1a-e. The test at 100% value is the reference in which no dynamic derivative values were altered from the predicted baseline values; it is used to determine the effect the altered derivative

Table 5
Results for Modified Clp Values

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	10.5+	45+ sec	13000+ ft	no sign of recovery	8
300	10.5+	45+ sec	13000+ ft	no sign of recovery	8
200	6	34 sec	11000 ft	slow damping	6
150	5	28.5 sec	9500 ft	fast damping	5
125	4.5	27 sec	8500 ft	fast damping	5
115	5	26 sec	8000 ft	fast damping	5
110	5	26 sec	8000 ft	noticeable differences	4
105	4	25 sec	8000 ft	small differences	3
100	**4**	**24 sec**	**7000 ft**	**Reference**	**0**
90	4	24 sec	7000 ft	slight differences	2
75	4	24 sec	7000 ft	small differences	3
50	4	23 sec	7000 ft	noticeable differences	4
0	3	17 sec	5000 ft	slow damping	6
-100	3	12.5 sec	3500 ft	very slow damping	7
-200	2	9 sec	N/A	continuous roll 15 sec	8

value (percentage) have on the flight characteristics. This table shows that even minor alterations to the Clp value have noticeable effects on the flight characteristics. Even small increases in the dynamic derivative Clp increase the altitude lost during spin recovery. A mere increase of 5% (or multiplied by 105%) requires an additional 1000 ft for spin recovery. Altitude loss during spin recovery is of significance because it is the determining factor in whether a pilot will remain with the aircraft through spin recovery or eject and lose the aircraft. The F/A-18E/F NATOPS emergency procedures call out 6,000 ft above ground level as the ejection decision point. If the aircraft is not fully recovered at this altitude the pilot must initiate ejection (reference 21). However, during flight testing most intentional spin procedures are initiated at high altitudes and an unexpected loss in altitude during spin recovery would cause uncertainty as to the best recovery procedures and require extensive additions to the test plans. As the value of Clp is increased further to 200% of it's baseline value the altitude loss during spin recovery increases to 11,000 ft, indicating a full 4,000 ft more altitude is needed to recover than expected if the dynamic derivative baseline value was in error to that degree. Further, the extremes of 300-400% increases to Clp's value do not allow the aircraft to recover at all. The aircraft was designed, and test plans were written, assuming the aircraft would recover in 7,000 ft for this spin profile. If the value of Clp that was extrapolated from wind tunnel test results was inaccurately low, flight testing would become increasingly more dangerous with the amount of error in this prediction and unknown risks would certainly be inherent in the program. However, it should be noted that when this dynamic derivative value was reduced the flight characteristics did not change significantly until the reduction was 100% lower than it's original value. Within these decreased values of Clp the effect on flight characteristic changes were minimal. It took essentially the same amount of time, altitude, and number of spins to recover. With this result in mind it can be assumed that if one must extrapolate a value for Clp from a variety of possible values it would be more conservative to err on the high side. Predicting Clp to be a greater value then it actually is would lead to assumptions that spin recovery would require more altitude, therefore providing the pilot with a safe prediction by recovering quicker then expected. While the most ideal solution would be to accurately predict the value of Clp, until that is possible it seems that erring on the high side is the most conservative and safest method of planning. Additionally, since even small errors in the value of Clp cause noticeable differences in flight characteristics there is a great need to predict this derivative with a high level of accuracy.

Table 6 depicts the results of the flight simulation workstation test when altered values (percentages) of Clr (rolling moment due to yaw) were flown through the spin profile. The graphical results from this test are presented in Appendix figures A2a-d. This

Table 6
Results for Modified Clr Values

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	9.5+	45+ sec	14000+ ft	no sign of recovery	8
300	9.5+	45+ sec	14000+ ft	no sign of recovery	8
200	6	32 sec	10000 ft	slow damping	6
150	4	25 sec	8000 ft	noticeable differences	4
125	4	25 sec	8000 ft	small differences	3
110	4	24 sec	7000 ft	slight differences	2
100	**4**	**24 sec**	**7000 ft**	**Reference**	**0**
90	4	24 sec	7000 ft	slight differences	2
75	4	23 sec	7000 ft	small differences	3
50	4	23 sec	7000 ft	small differences	3
0	4	22.5 sec	7000 ft	small differences	3
-100	4	21 sec	6500 ft	fast damping	5
-200	3	15 sec	4000 ft	slow damping	6

table shows that minor alterations to the value of Clr have very little effect on the flight characteristics. Decreases in the value of Clr up to 200% below it's predicted value (multiplied by -100%) show noticeable differences in spin damping, but these differences do not significantly alter the number of spins, the time to recover, or the altitude lost during recovery. Increases to the value of Clr by 25% cause noticeable differences in flight characteristics, but do not further degrade until an increase of 100% is made. With modifications to Clr greater then 100% increased or 200% decreased the flight characteristics did change significantly and worsened rapidly, with more dramatic increases to altitude loss for increases to Clr verses decreases indicating the possibility of an unrecoverable spin. From this data it can be concluded that if Clr can be predicted within 25% of it's actual value small deviations in the actual verses predicted values will not significantly alter the expected flight characteristics. However, prediction errors over 100% off from the actual value for Clr will lead to unexpected and possibly terminal changes in the flight characteristics. In this case again it would be best to err on the high side during predictions since increases to the value of Clr did have more dramatic effects on the flight characteristics then did decreases. Predicting Clr to be a greater value then it actually is would lead to assumptions that the spin recovery would require more altitude, therefore providing the pilot with a safe prediction. While the most ideal solution would be to accurately predict the value of Clr, until that is possible it seems that erring on the high side is the most conservative and safest method of planning.

Table 7 depicts the results of the flight simulation workstation test when altered values (percentages) of $Cl\Omega$ (rolling moment due to rotation) were flown through the spin profile. The graphical results from this test are presented in Appendix figures A3a-e.

Table 7
Results for Modified ClΩ Values

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	3	19 sec	6000 ft	slow damping	6
300	4	24 sec	8000 ft	fast damping	5
200	4	23 sec	8000 ft	noticeable differences	4
150	4	23 sec	7000 ft	slight differences	2
125	4	23 sec	7000 ft	slight differences	2
110	4	23 sec	7000 ft	slight differences	2
100	**4**	**24 sec**	**7000 ft**	**Reference**	**0**
95	4	24 sec	7000 ft	slight differences	2
90	4	24 sec	7000 ft	small differences	3
85	4	25 sec	8000 ft	noticeable differences	4
80	4	25 sec	8000 ft	noticeable differences	4
75	5	26 sec	8500 ft	noticeable differences	4
50	5	26 sec	8500 ft	noticeable differences	4
0	5	28 sec	9000 ft	fast damping	5
-100	5.5	30 sec	9000 ft	slow damping	6
-200	11+	45+ sec	10000+ ft	no sign of recovery	8

This table shows that minor increases to the value of ClΩ have very little effect on the flight characteristics. For increases to ClΩ up to 200% above it's predicted value (multiplied by 300%) there are noticeable differences in the spin's damping, but these differences do not significantly alter the number of spins, the time to recover, or the altitude lost during recovery. Minor decreases to the value of ClΩ, with 15% reduction in it's value (multiplied by 85%) show noticeable changes in the flight characteristics, specifically by increasing altitude lost during recovery. These changes become even more pronounced with a 25% reduction in value, and further again with 100% reduction in value. With this data in hand it can be assumed that if one must calculate the value for ClΩ using inaccurate rolling and yawing derivative data it would be best to err on the low side. Predicting ClΩ to be a lesser value then it actually is would lead to assumptions that the spin recovery would require more altitude, therefore providing the pilot with a safe prediction. While the most ideal solution would be to accurately predict the value of ClΩ, until that is possible it seems that erring on the low side is the most conservative and safest method of planning.

Table 8 depicts the results of the flight simulation workstation test when altered values (percentages) of Cnp (yawing moment due to roll) were flown through the spin profile. The graphical results from this test are presented in Appendix figures A4a-d. This table shows that small and large decreases to the value of Cnp have very little effect on the flight characteristics. For decreases to Cnp up to 300% below it's predicted value (multiplied by -200%) there are small differences in the spin's damping characteristics, but these differences do not significantly alter the number of spins, the time to recover, or the altitude lost during recovery. However, with increases to the value of Cnp of only 50% (multiplied by 150%) there is a 1000 ft increase in the altitude lost during spin recovery.

Table 8
Results for Modified Cnp Values

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	5	29 sec	9000 ft	fast damping	5
300	5	25 sec	8000 ft	noticeable differences	4
200	5	25 sec	8000 ft	noticeable differences	4
150	4	25 sec	8000 ft	small differences	3
125	4	24 sec	7000 ft	slight differences	2
110	4	24 sec	7000 ft	slight differences	2
100	**4**	**24 sec**	**7000 ft**	**Reference**	**0**
90	4	24 sec	7000 ft	unnoticeable differences	1
75	4	24 sec	7000 ft	unnoticeable differences	1
50	4	24 sec	7000 ft	unnoticeable differences	1
0	4	24.5 sec	7000 ft	small differences	3
-100	4	23.5 sec	7000 ft	small differences	3
-200	4	23.5 sec	7000 ft	small differences	3

This change in flight characteristics is not further pronounced until the value of Cnp is increased by 300% (multiplied by 400%) at which point the altitude lost increases by another 1000 ft. With this data in hand it can be assumed that if one must extrapolate a value for Cnp from a variety of possible values it would be best to err on the high side. Predicting Cnp to be a higher value then it actually is would lead to assumptions that the spin recovery would require more altitude, therefore providing the pilot with a safe prediction. While the most ideal solution would be to accurately predict the value of Cnp, until that is possible it seems that erring on the high side is the most conservative and safest method of planning.

Table 9 depicts the results of the flight simulation workstation test when altered values (percentages) of Cnr (yawing moment due to yaw) were flown through the spin profile. The graphical results from this test are presented in Appendix figures A5a-d.

Table 9
Results for Modified Cnr Values

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	4	23 sec	7000 ft	noticeable differences	4
300	4	23 sec	7000 ft	small differences	3
200	4	24 sec	7000 ft	small differences	3
150	4	24 sec	7000 ft	slight differences	2
125	4	24 sec	7000 ft	slight differences	2
110	4	24 sec	7000 ft	unnoticeable differences	1
100	**4**	**24 sec**	**7000 ft**	**Reference**	**0**
90	4	24 sec	7000 ft	unnoticeable differences	1
75	4	24 sec	7000 ft	slight differences	2
50	4.5	26 sec	8000 ft	noticeable differences	4
0	4.5	26.5 sec	8000 ft	fast damping	5
-100	5	25.5 sec	8500 ft	fast damping	5
-200	5	26.5 sec	8000 ft	fast damping	5

This table shows that minor alterations to the value of Cnr have very little effect on the flight characteristics. When the value of Cnr is increased up to 300% above it's predicted value (multiplied by 400%) there are noticeable differences in the damping, but these differences do not significantly alter the number of spins, the time to recover, or the altitude lost during recovery. However, decreasing the value of Cnr by 50% from its baseline value did alter the flight characteristics, specifically by requiring an additional 1000 ft to recover from the spin. But, further decreasing the value of Cnr did not significantly add to the recover altitude losses, and 1500 ft additional recovery altitude was the worst case scenario for modifications to Cnr up to 300%. From this data it can be concluded that inaccurately predicting the value of Cnr up to 300% will not cause significant differences in the expected verses actual flight characteristics.

Table 10 depicts the results of the flight simulation workstation test when altered values (percentages) of $Cn\Omega$ (yawing moment due to rotation) were flown through the spin profile. The graphical results from this test are presented in Appendix figures A6a-e. This table shows that minor increases to the value of $Cn\Omega$ have very little effect on the flight characteristics. However, for an increase to the value of $Cn\Omega$ of 100% above it's predicted value (multiplied by 200%) there is actually a positive effect on the flight characteristics, as the spin recovery requires less time and number of spins. Additionally, as the value of $Cn\Omega$ was further increased the spin characteristics further improved. Modifications to this derivative are the first results to show positive effects on the flight characteristics. This means that if the actual value of $Cn\Omega$ inherent to the aircraft's design could actually be increased the spin characteristics would be slightly better, but for flight test planning purposes this result could pose a serious risk to the pilot. If the predicted

Table 10
Results for Modified $Cn\Omega$ Values

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	2	16.5 sec	5000 ft	slow damping	6
300	3	18 sec	5000 ft	slow damping	6
200	3	21 sec	7000 ft	fast damping	5
150	4	23 sec	7000 ft	noticeable differences	4
125	4	23.5 sec	7000 ft	small differences	3
110	4	23.5 sec	7000 ft	small differences	3
100	**4**	**24 sec**	**7000 ft**	**Reference**	**0**
95	4	24 sec	7500 ft	small differences	3
90	5	26 sec	8000 ft	noticeable differences	4
85	5	25.5 sec	8000 ft	noticeable differences	4
80	5	26.5 sec	8500 ft	noticeable differences	4
75	5	27 sec	9000 ft	fast damping	5
50	5	26 sec	8000 ft	fast damping	5
0	6	29 sec	9000 ft	slow damping	6
-100	8	34 sec	11000 ft	very slow damping	7
-200	9	42 sec	14000 ft	very slow damping	7

value of $Cn\Omega$ is significantly higher then the actual value inherent to the aircraft the test pilot will expect the aircraft to recover sooner then it actually will. Looking at the decreases to the value of $Cn\Omega$, it can be seen that changes of only 10% reduction in value (multiplied by 90%) produces noticeable changes in the flight characteristics and altitude lost during recovery. The results slowly worsen until the derivative is reduced by 200% at which point the change in flight characteristics become much more pronounced, and further again at 300% reduction in value. With this data in hand it can be concluded that if one must calculate the value for $Cn\Omega$ from inaccurate rolling and yawing derivatives it would be best to err on the low side. Predicting $Cn\Omega$ to be a lesser value then it actually is would lead to assumptions that the spin recovery would require more altitude, therefore providing the pilot with a safe prediction. As mentioned above, predictions of $Cn\Omega$ that are too high could lead to unexpected and dangerous flight test results. While the most ideal solution would be to accurately predict the value of $Cn\Omega$, until that is possible it seems that erring on the low side is the most conservative and safest method of planning.

Table 11 depicts the results of the flight simulation workstation test when altered values (percentages) for all dynamic derivative values tested. The graphical results from this test are presented in Appendix figures A7a-d. In these tests all derivative values are altered equally, as if all predicted values were 10% under the actual value, or 50% over the actual value, etc. Obviously, this scenario is highly unlikely, especially in the case of very large variations to the derivative values. While it is likely that all predicted derivative values are inaccurate by some amount, it's unlikely that they would all be off by the same magnitude.

For the sake of thorough testing this test was conducted to see what would happen if all values were inaccurate, additionally it was not possible within the scope of this test to

Table 11
Results for Modification to all Derivative Values:
(Clp, Clr, ClΩ, Cnp, Cnr, CnΩ all changed by given percent)

PERCENT	# SPINS	RCVRY TIME	ALT. LOST	COMMENTS	CR
400	2.5	18 sec	5000 ft	slow damping	6
300	4	21 sec	6000 ft	slow damping	6
200	5	28 sec	9000 ft	slow damping	6
150	4	25 sec	8000 ft	Small differences	3
125	4	25 sec	8000 ft	Small differences	3
110	4	24 sec	7000 ft	Slight differences	2
100	**4**	**24** sec	**7000** ft	**reference**	**0**
90	4	24 sec	7000 ft	Slight differences	2
75	5	25 sec	8000 ft	noticeable differences	4
50	5	25 sec	8000 ft	fast damping	5
25	4	19 sec	6000 ft	fast damping	5
0	3	16 sec	4000 ft	fast damping	5

alter all derivative values by different magnitudes for an endless array of flight simulation test runs. This table shows that minor alterations to all derivative values have little effect on the flight characteristics. With 10% alteration to the derivative values (increased and decreased) the differences do not alter the number of spins, the time to recover, or the altitude lost during recovery. Alterations of up to 50% (increased and decreased) did change the flight characteristics, specifically by requiring an additional 1000 ft to recover from the spin. Further analysis of these test results beyond 50% alteration does not seem necessary due to the extreme rarity of this occurrence.

CHAPTER 3: CONCLUSIONS

Dynamic derivative values must be calculated with more accuracy to evolve the next generation of modern aircraft with more precision in flight characteristic predictions. Test results were compared and analyzed to identify derivative alterations that caused the most significant changes in flight characteristics with the least error in their predicted values. For several derivatives, if the predicted value was inaccurate by only small amounts, which is highly likely, the actual flight characteristics varied noticeably from those expected. Data analysis revealed that Clp is the most critical variable to predict accurately. With predicted Clp errors of only 5% there will be noticeable differences in the spin characteristics of the aircraft. Errors beyond 5% will substantially increase the effects on predicted characteristics. The second most critical derivative to accurately predict is CnΩ, which leads to changes in the flight characteristics with only a 10% negative error in the predicted value. ClΩ also shows changes to flight characteristics with only 15% negative error and is a necessary value to be predicted accurately. The rotation derivatives (ClΩ and CnΩ) have high sensitivities to inaccurate information since these values are summations of the rolling and yawing derivatives and therefore expound on any errors present. Minor errors in the value of Clr will prove to have little affect on the flight characteristics unless the error is beyond 25% positive or negative. This derivative is not as crucial for precise measuring and predictions as long as estimations are within these bounds. And finally, Cnp and Cnr have little effect on flight characteristics if their values are inaccurately predicted. The priority list provided in table 12 gives the relative degree to accurately predict each dynamic derivative. This priority ordering considers the

Table 12
Prediction Priority List

Priority	Derivative	Accuracy Required
1	Clp	5%
2	CnΩ	10%
3	ClΩ	15%
4	Clr	25%
5	Cnp	50%
6	Cnr	50%

magnitude of effect these errors have on flight characteristics, concentrating largely on altitude lost during spin recovery, and the effects of altering the derivatives by both increased and decreased values.

Table 13 is a review of all notable results from each test. Two error bounds were established, one indicating extreme flight differences (CR 7-8) where recovery of the aircraft was questionable at best, and the other indicating noticeable differences (CR 4-6) where spin recovery was significantly different than expected with the predicted derivative values. The term CR is defined and explained in table 4. Table 13 shows the significant results from all tests performed. Several parameters are given for each dynamic derivative tested. As mentioned above two error bounds were established for those with a CR value of 4-6, and another for those with a CR value of 7-8. This table shows the percentage that each derivative value tested would have to be inaccurately predicted to fall into each of these categories. These values vary slightly from those in table 12 because this table primarily compares CR values based on time to recover the aircraft while the previous table concentrated more on altitude loss. The results in table 13 show that inaccurate predictions for the value of Clp will lead to noticeable differences in flight characteristics

Table 13
Comparison of Test Results

Derivative Changed	Noticeable Differences		Extreme Differences		Common Deviation	Max Deviation
Clp	+10%*	-50%	+200%	-200%	+85%	-375%
Clr	+50%	-200%	+200%	N/A**	+260%	+375%
ClΩ	+100%	-15%	N/A	-300%	±50%	+1100%
Cnp	+100%	N/A	N/A	N/A	N/A	N/A
Cnr	+300%	-50%	N/A	N/A	N/A	N/A
CnΩ	+50%	-10%	N/A	-200%	N/A	N/A
All	+100%	-25%	N/A	N/A	N/A	N/A

* This value represents the amount the derivative was altered (a 10% alteration corresponds to the baseline derivative value being multiplied by 110%).
** N/A indicates that the CR value never reached that magnitude during these tests, or that data were not available for this evaluation.

with a 10% increase or 50% decrease in value, and will lead to extreme differences (possibly unrecoverable) if the predicted values are 200% off from the actual aircraft's derivative values. Two additional parameters are presented: common deviation and maximum deviation. These numbers were extracted from figures 1-3 for the F/A-18E/F wind tunnel and flight simulation predicted derivative values. Values are not given for all derivatives because figures were not available for them. The first parameter, common deviation, is an extrapolation from these figures showing the percent error between the worst case wind tunnel prediction and the flight simulation database prediction at 20 degrees AOA. This AOA value was considered to be 'common' since this area has relatively small errors in predicted versus actual values. Figures 1-3 indicate that dynamic derivatives are well predicted in the 0 to 20 degree AOA range. The second parameter, maximum error, was also extrapolated from figures 1-3. Each figure shows an anomaly in which a wind tunnel prediction had the largest deviation from the flight simulation value. It should be noted that these large peaks in data were all received from the forced oscillation wind tunnel. Looking at the F/A-18C/D and F/A-18E/F data sets, it is apparent the data peaks were considered in the flight simulation database values, and that the trend (or slope) was often implemented to a limited amount. However, the F/A-18C/D PID tests do not indicate that these trends are accurate.

The two deviation columns in table 13, listing deviations between wind tunnel predictions and flight simulation database values, are of significant importance. Investigating the data from the F/A-18 wind tunnel tests shown in figures 1-3 it was possible to determine the common and/or maximum error that can be expected between a wind tunnel test and the flight simulation database used in aircraft design and test planning. The percentage errors resulting from the flight simulation spin analysis in this report were compared to those that are common (and maximum) in predicted values. The flight simulation spin tests registered that errors as low as 10% can cause noticeable differences in the aircraft's response. Upon final analysis of the percentages leading to modified flight characteristics in tables 12 and 13, and comparing them to their corresponding deviation errors in figures 1-3, shows that the prediction errors causing flight differences are common during wind tunnel tests for each variable. For example, it is common to have prediction errors in the value of Clp that are approximately +85% off from the values used in flight simulation, and those errors on the order of 5% (from table 12) and 10% (from table 13) will generate noticeable differences in flight characteristics with aircraft designed and tested with these inaccuracies. Furthermore, a common prediction error for Clr is found to be +260%, which is greater than the prediction error that will lead to extreme (possibly unrecoverable) differences in flight characteristics. Comparing the maximum deviations for each data set further highlights the fact that modified flight characteristics are expected in flight when applying these inaccurately predicted dynamic derivative values. One can deduce that there were noticeable differences in the expected versus actual flight characteristics when the test pilot entered spin conditions in the test aircraft. The F/A-18E/F spin testing program was fortunate no aircraft have been lost due to these errors. Do we presume these values were not significant enough to lead to an unrecoverable spin? One should keep in mind that this information was not known before the first spin was entered by a pilot. It is the opinion of this author that accepting flight simulation data used for aircraft design, test planning, and pilot proficiency with these inaccuracies will eventually lead to an unexpected and unrecoverable spin condition. This analysis proves the need for precise methods of generating predicted dynamic derivative values.

We should not accept these significant changes in spin characteristics as found when the dynamic derivatives were altered through error ranges that are common with current prediction methods. All of the derivatives with data available (Clp, Clr, and ClΩ) showed extreme (possibly unrecoverable) differences in flight characteristics during spins within the maximum predicted error range, and also displayed noticeable flight differences within a common error range. Additionally, the derivative Clr showed that extreme differences in flight characteristics are possible with common errors in the prediction of its value. Relying on these inadequate predictions will lead to unexpected flight characteristics during spin recovery, by changing the number of spins, the amount of time passed, and the altitude lost prior to spin recover. Relying on this data could put the pilot into an unrecoverable spin and emergency condition without proper planning for the situation.

The data presented in table 12 shows the accuracy of dynamic derivative predictions required to get expected (or close to expected) losses in altitude during spin recovery. The data presented in table 13 shows the accuracy of dynamic derivative predictions required to get expected (or near expected) values in time elapsed between spin initiation and hands free spin recovery. Both tables take other factors into account, but are largely based on these variables. Table 14 combines these predictions to give a complete picture of the accuracy required relative to which variable you wish to accurately predict. If one wishes both variables to be as accurate as possible for a given dynamic derivative, they must choose the lowest value presented in table 14. The trend for the altitude based and time based accuracies required is remarkably similar, but does show in two cases that more accurate dynamic derivative values are required to adequately predict altitude loss during spin recovery. The results of table 14 show that the derivative that requires the highest degree of accuracy in its predictions is undoubtedly Clp, followed by CnΩ, ClΩ, and then Clr. The values of the remaining derivatives seem adequate if they are predicted within 50% of their actual value.

Table 14
Prediction Accuracy Required

Priority	Derivative	Altitude Based Accuracy Required	Time Based Accuracy Required
1	Clp	5%	10%
2	Clr	25%	50%
3	ClΩ	15%	15%
4	Cnp	50%	100%
5	Cnr	50%	50%
6	CnΩ	10%	10%

The values that are received from current dynamic derivative prediction methods generate inaccurate common errors, where precise values are required for aircraft design. For this reason the flight control laws must be written for less than optimal performance. The expected flying qualities will be incorrect to some degree, and the training methods for spin recovery may not be optimal. To solve this problem more research should be conducted to look into better methods of predicting dynamic derivative values. This research should entail a detailed concentration into the AOA range above 20 deg where the data is most questionable.

The results from this test and evaluation imply that the forced oscillation wind tunnel generates the most questionable results of those displayed. This is primarily based on the fact that the maximum deviation on each figure was a direct result of that test. The most evident deviations in the data are concentrated above the 20 degree AOA region. It can also be seen in the F/A-18C results from figures 1-3 that this maximum deviation was used to help extrapolate the MDA database although it does not seem to influence the F/A-18E MDA database, possibly due to lessons learned. This could be one reason why the F/A-18C aircraft has experienced such extensive problems with unexpected spin entries and uncertainty as to the most effective spin recovery procedures.

CHAPTER 4: RECOMMENDATIONS

The following recommendations are solely the opinion of the author and do not necessarily reflect the opinion of the United States Navy or the F/A-18 Program Office.

1. The first and primary recommendation is to increase research and development funding into new methods to more accurately predict dynamic derivative values. There are wide ranges of possible new methods and/or updates to existing methods. One should keep in mind that several methods combined may be required to make accurate predictions, as certain tests may be better at predicting a specific derivative, and other tests may be best for predicting limited parts of the derivative value throughout the AOA range tested. As discussed in this report, the prediction methods between 0 and 20 deg AOA seem reasonably accurate (although a full test of their inaccuracy effects was not conducted), therefore research should concentrate on the AOA range above 20 deg where the prediction data is most questionable. The following are ideas for possible new and/or modified prediction methods:

   a) There were several Science and Technology (S&T) projects conducted during the F/A-18E/F development to further examine this issue, and to examine alternate possibilities for predicting dynamic derivative values. Two specific projects were the F/A-18E/F RPV (Remotely Piloted Vehicle) and the F/A-18E/F NASA Drop Model. The purpose of these tests was to more accurately portray actual flight conditions including full freedom of motion in all axes, and rotation rates similar to those experienced in flight. This type of testing eliminates errors induced by wind tunnels themselves with flow disturbances.

These are common limitations to current prediction methods that could be overcome with free flight methods of data prediction.

1) The RPV was a 17.5% scale model of the aircraft, which was designed like a wind tunnel model to be aerodynamically identical to the full size aircraft. It was powered by two small jet engines and was capable of flight up to 150 knots. This model was fully instrumented to directly obtain static and dynamic derivative data in flight. However, the aircraft was crashed after only seven flights and in this time the program was not capable of obtaining enough useful data to be implemented into the flight simulation database. The data that was received prior to aircraft loss was promising and proved that this method of predicting dynamic derivative values would be at least as accurate as the current methods if not better.
2) The Drop Model was a 22% model of the full size aircraft. It was dynamically scaled to accurately represent the full scale aircraft by geometric as well as inertial scaling. This aircraft was also fully instrumented to obtain static and dynamic derivative values in flight. In addition it was scaled in time, with flight controls actuator responses at an accurate rate to represent the full size aircraft. This vehicle was not powered, but dropped from a helicopter at scaled altitudes up to 15,000 ft and controlled remotely through a series of maneuvers as it fell through the sky. This aircraft was also lost, due to a failure in the flight termination parachute, which was supposed to keep it afloat in the sea until retrieval by boat was possible. Again not enough meaningful data was received to

modify the flight control laws, but the data that was received also proved promising in accurately predicting dynamic derivative values. The results showed that drop model tests can be used to accurately predict high AOA flight characteristics. The F/A-18E/F drop model data exhibited excellent correlation with full-scale airplane results, even during highly dynamic maneuvers including spins (reference 18).

Although the data from these tests was never fully expanded they did prove credible and should be considered for future aircraft development programs.

b) More emphasis on CFD (Computational Fluid Dynamics) to obtain aerodynamic coefficients. CFD is a mathematical method of generating the same data using computers to analyze the airflow forces and moments that result from aircraft motions. The tests that have been conducted using this prediction method have proven to be quite accurate. This method currently has very limited use mainly because of the extreme amount of computational power required for each analyzed flight condition and because computerizing airflow characteristics is a very detailed and currently uncertain process. Computational power is a rapidly growing field with seemingly endless technology advancements in computer development. CFD may eventually prove to be a very useful tool for more accurately predicting dynamic derivative values. As with the RPV and Drop Model this method eliminates many of the motion limitations inherent in wind tunnel testing and wind tunnel induced airflow disturbances.

c) Continue to fund the programs that support technological advancements in wind tunnel designs like: laser Doppler velocimetry, making it possible to determine velocities more precisely with light beams, and 'smart walls' which expand and contract in ingenious ways to remove the distorting effects walls can have on the tunnel's airflow (reference 5). State of the art wind tunnels could increase the accuracy of an already accepted method of predicting aerodynamic coefficients. These advancements should be closely monitored and their data should be verified and validated against known coefficients from an existing aircraft platform.

d) The aircraft models used in dynamic wind tunnel test have to undergo high frequency and amplitude motions and therefore must be as light and stiff as possible to reduce induced airflow disturbance and aeroelastic effects. While these effects may never be eliminated new materials are constantly being developed which have potential for providing more suitable wind tunnel models. With the creation of each new wind tunnel model new materials should be analyzed to see if benefits could be gained by using them.

e) Dynamic wind tunnel tests often have problems testing at the natural frequency of the oscillating system and may not be able to collect useful data in this region (reference 6). Tests should be conducted to determine what region is 'invalid' for each individual wind tunnel facility. The data in these regions should be eliminated from the results prior to being evaluated for implementation in the flight simulation database. This is most likely the situation that is occurring in the forced oscillation data in figures 1-3, as the value for each derivative seems to be highly inaccurate at approximately 40 deg AOA. If the results from this test were modified to eliminate any predictions in this region the remainder of the data may prove to be exceptional and increase the acceptance of its values.

f) Further evaluation of the available mathematical implementation methods should be conducted, as well as additional research into new mathematical models. The raw data as collected from dynamic wind tunnel tests does not produce intelligible results without a method of combining these results and depicting their effect on the aircraft's flight mechanics. Flight simulators are the primary method of depicting this data, using mathematical correlations between the variables to combine them into flight profiles. The method of implementing dynamic test data has been the topic of many studies, several examples are given in references 7-10 with topics including: spin prediction techniques, high AOA stability characteristics, the aerodynamic characteristics in aircraft dynamics, and model of non-planar aircraft dynamics. Implementation of this highly non-linear and possibly time dependant data is certainly not an easy task. Again it should be noted that data from different wind tunnel facilities may be best implemented using different mathematical models, or there may be one all encompassing model, which combines all data more effectively to produce more accurate predictions using existing wind tunnels and data.

2. Developing new methods to predict dynamic derivative values, and fully evaluating these methods until a perfect method is found, will undoubtedly take many years if

not decades to complete. Therefore, there must be a plan to continue using the current prediction methods with the known inaccuracies they provide until better methods are available. There are several approaches that can be followed to increase flight safety and reduce the overall life cycle cost of the aircraft while utilizing the available dynamic derivative values.

a) Aircraft designers must build on lessons learned from previous aircraft designs prior to aircraft construction relying on known actual flight characteristics vice relying solely on wind tunnel predictions. Additionally, aircraft should be designed with an open architecture whenever possible, allowing for future modifications if/when needed.

    1) A case in point for open architecture designing is from the F/A-18E/F wing. During flight test efforts this aircraft experienced a phenomenon called 'wing drop' in the heart of it's operating envelope, which greatly reduced the mission effectiveness of the aircraft. When this problem was found engineers determined that to eliminate the problem completely the aircraft wing should be re-designed to induce a twist in the leading edge of the airfoil. However, this was not practical so late in the aircraft development because full production rigs had already been developed for the current wing design and the cost of replacing them would be astronomical. If designers had kept a more open mind to possible problems that might arise which had never been predicted by wind tunnel results they may not have created the aircraft rig so quickly. Of course this is a major trade off that would need to be evaluated, by allowing a more open

architecture until late in the aircraft test phase it would take much more lead time to begin a full rate production of the aircraft.

2) One region that is generally left open for late modifications is the aircraft's software, including the flight control laws. Thankfully, software allows for relatively quick modifications without a major impact on aircraft producability. It is very important that the flight control laws always remain an open architecture item even after full production has begun, as unpredicted flight characteristics can be found even after a full test program is completed, and these characteristics can often be fixed with an update to the software. This is apparent in the case of the F/A-18C/D, which is currently undergoing an update to its control laws to improve the spin characteristics.

b) Spin flight testing in the aircraft should be delayed until late in the test program. This will allow for direct measurements of the derivative values through PID testing, and validation and verification of the flight simulation database prior to spin entry. This recommendation is based on the assumption that PID analysis more accurately depicts the aircraft's derivative values than wind tunnel testing. Further evaluations should be conducted to assure that this is in fact true. If this is proven, the flight simulation database should be modified with the more accurate PID results, and evaluations should be made to determine if changes to the flight control laws and/or recommended spin recovery techniques should be made before the first spin flight test is conducted.

c) Pilot training and proficiency flights are often flown in flight simulators due to the lesser cost to operate the simulator verses the real aircraft. Training and proficiency for spins should also be delayed until PID data has been implemented into the simulation database. If this is not possible, the pilot should be fully briefed on the possible prediction inaccuracies and unexpected flight characteristics that could result. The pilot should always be informed as to what is expected in flight, as well as the worst case scenario and plan if the predictions are wrong. The pilot should be the first to know when unexpected flight characteristics are encountered during a spin recovery.

d) The test program should plan for additional spin testing with the knowledge that spin characteristics will be different than expected due to the inaccuracies in current dynamic derivative prediction methods. These tests should allow for testing of several recovery techniques in flight, without relying on the flight simulation's prediction of the best recovery method. If the F/A-18C/D program had allowed for this they may have saved many lives, aircraft, and much money, by predicting the best spin recovery technique prior to the aircraft being released to the fleet. Additionally, a training program should be established for fleet pilots to experience out of control flight characteristics in a safe manner so they are not inexperienced in this region should they unintentionally encounter it.

3. It is inherent that a research project of this magnitude can not solve all problems with limitless accuracy. Therefore, further evaluations are recommended in the following areas.

a) This analysis was based on the results received through a flight simulation evaluation. The evaluation was designed to provide results that would be controlled so that they could be compared to one another. Specifically, dynamic derivative values were altered individually instead of in groups, and their values were altered by multiples (or percents) of their baseline predicted values instead of in logical manipulations of the curves themselves. This method does not provide the most realistic derivative curves for comparison with prediction methods. For this reason more research should also be conducted in the use of simulation capabilities to better alter these derivative values and provide more representative results.

b) Further experiments could be done to evaluate the longitudinal dynamic derivative effects on spin characteristics. These coefficients were neglected to reduce the scope of this test, but certainly have inaccuracies in their prediction values as well.

c) Further evaluations should also be conducted to examine the effect of inaccuracies in dynamic derivative values below 20 deg AOA, and even for inaccuracies in static derivative values. Static derivatives are often assumed to be easily predicted with reasonable accuracy, but there must be discrepancies between different wind tunnel facility values to some degree. Static derivatives are the basis of the flight simulation database and it would be hard to have good dynamic predictions if the underlying static data is inaccurate. The adequacy of static wind tunnel data could be the basis of a separate study, which would surely provide helpful insight to this evaluation of dynamic data.

d) This evaluation, like all others, was limited in scope, including limitations to the aircraft configurations that were tested, and initial conditions of the test. Certainly more tests could be run with varied inputs for these values and may reach different conclusions then were reached here.

e) As mentioned above, further evaluations should be conducted into the adequacy of PID test results. If PID is the ultimate truth data in static and dynamic derivative values it's uses would be limitless, however if this data itself has inaccuracies it's uses should be limited and controlled.

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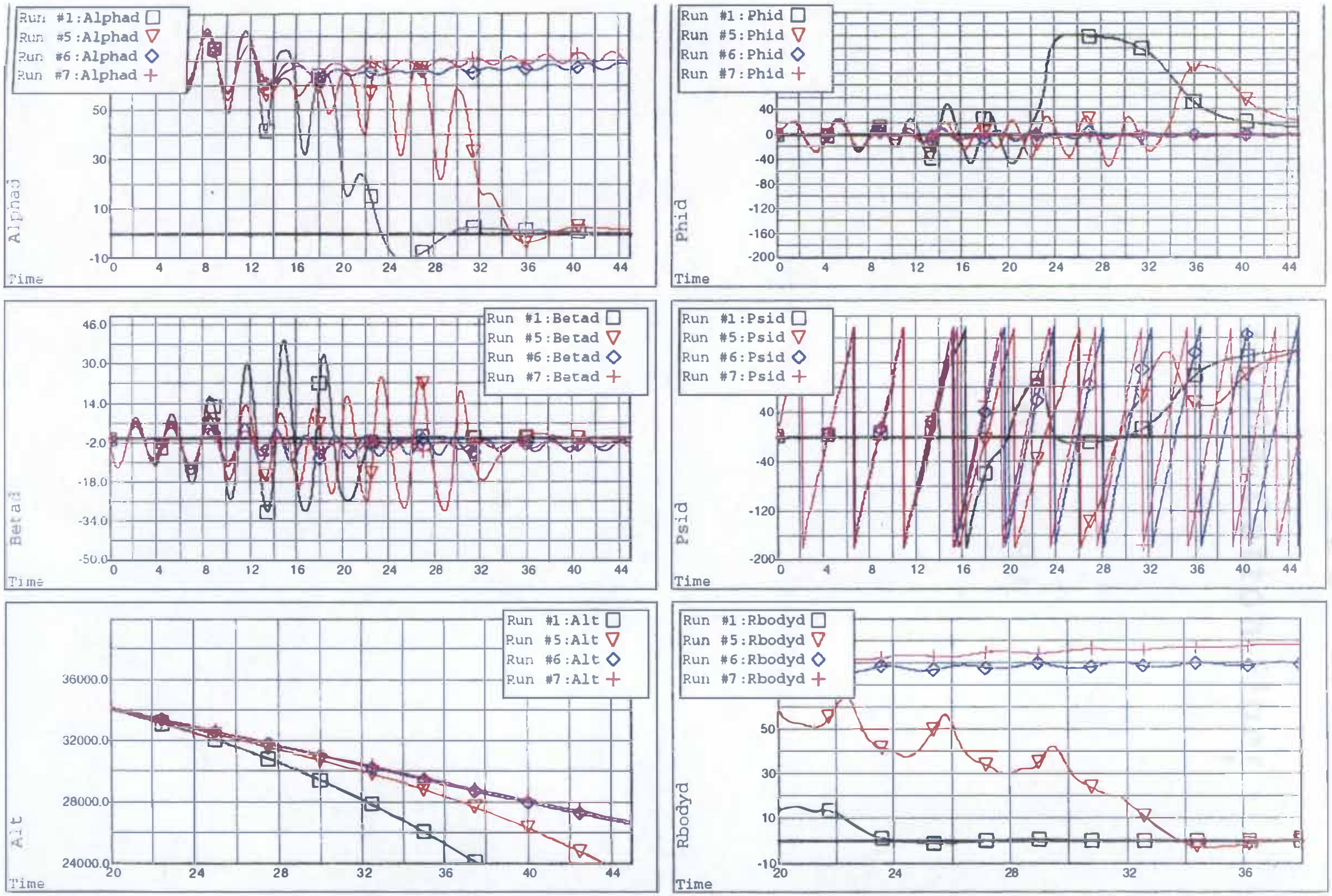
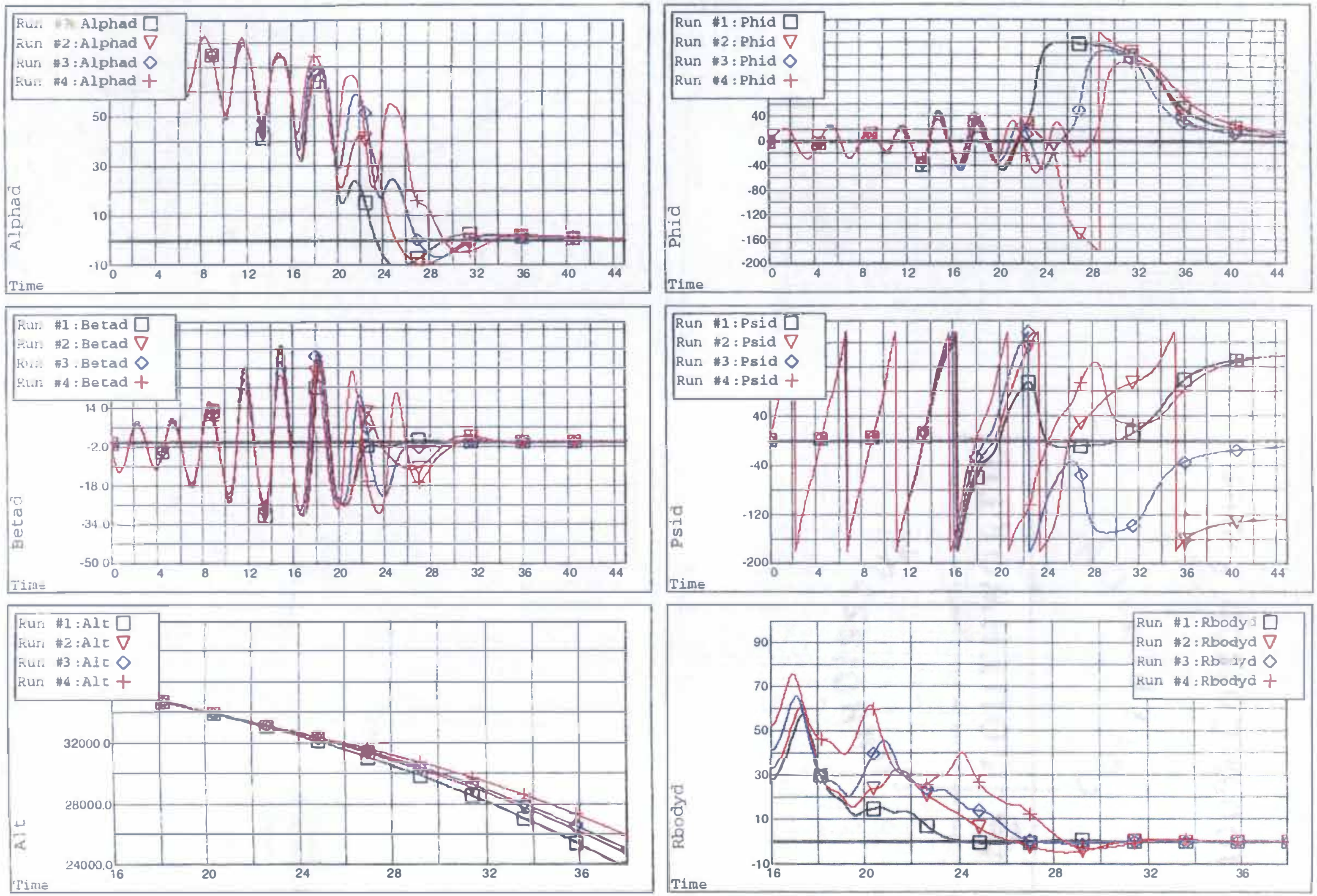
APPENDIX



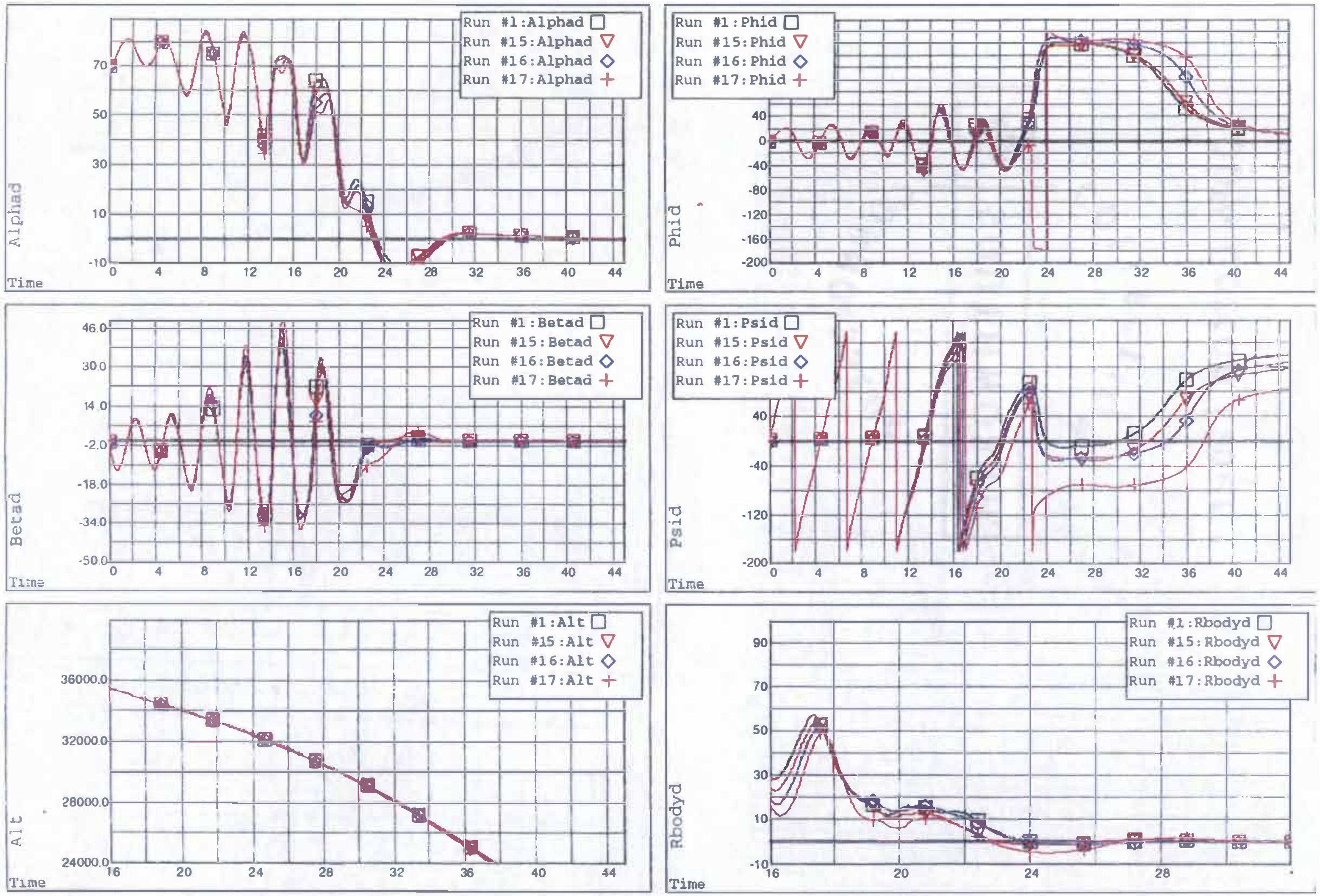
%(clp,clr,clo)= (100,100,100) (200,100,100) (300,100,100) (400,100,100)

Figure A1-a
Clp % of predicted value (400% to -200%)



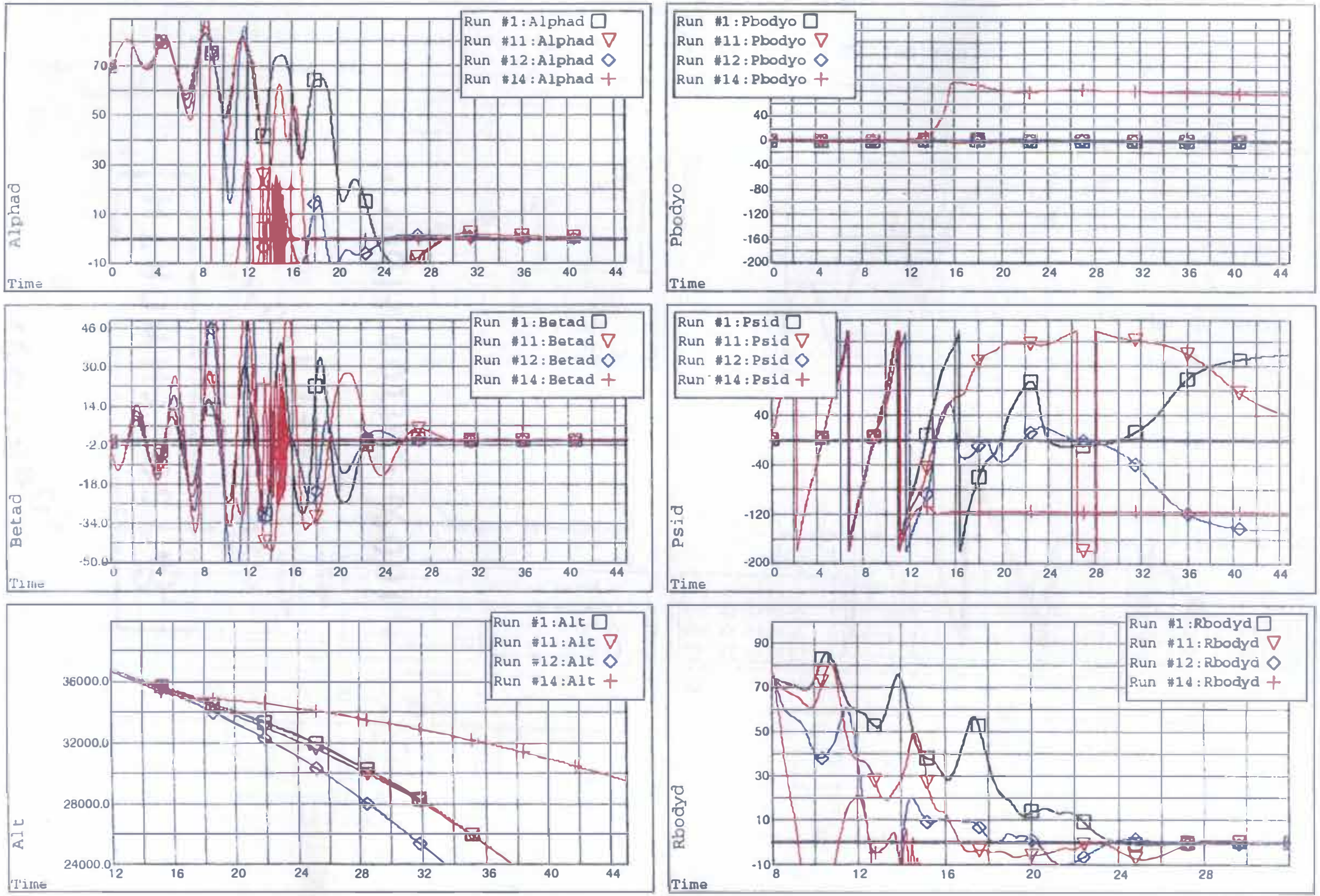
%(clp,clr,clo)= (100,100,100) (110,100,100) (125,100,100) (150,100,100)

Figure A1-b
Clp % of predicted value (400% to -200%)



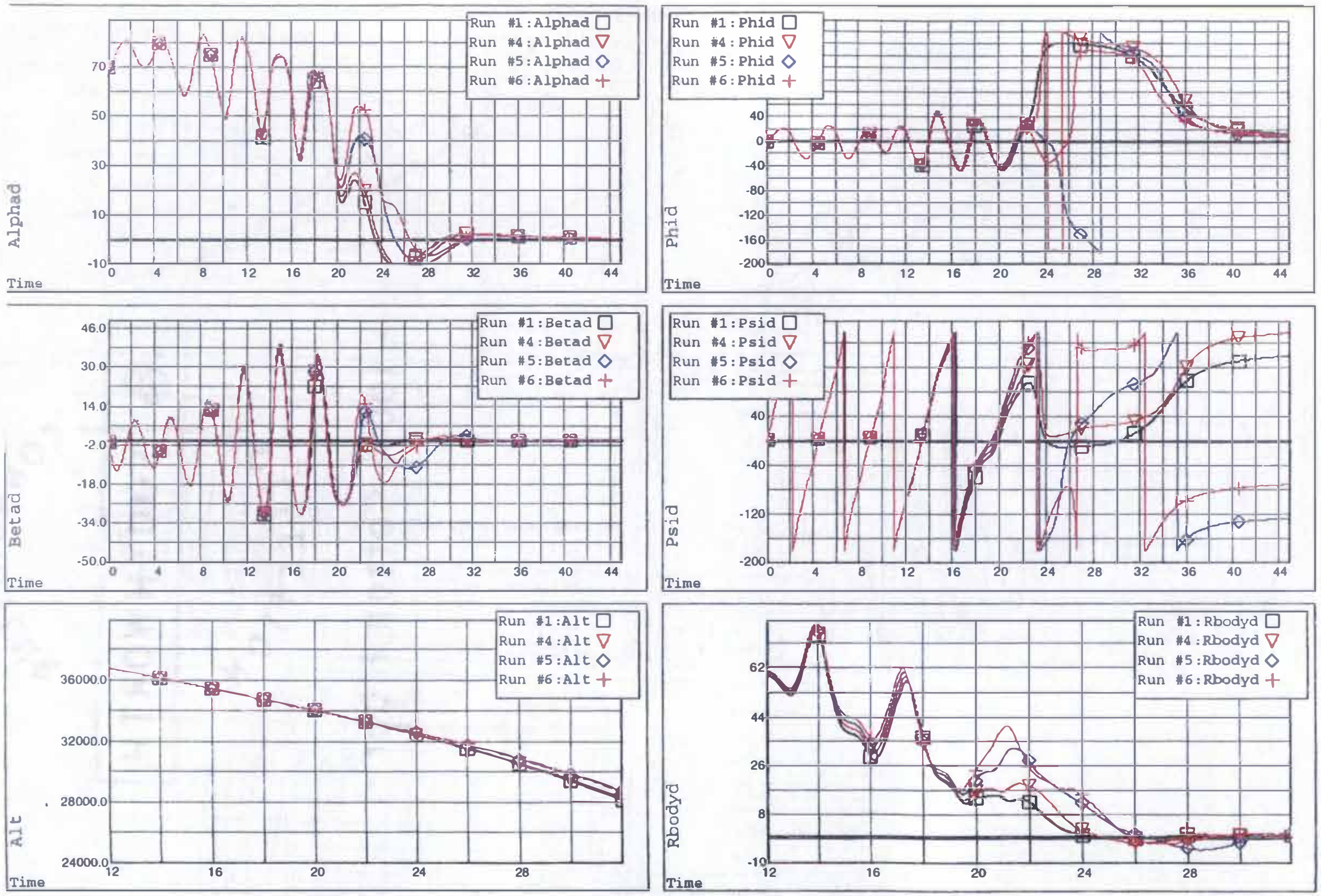
%(clp,clr,clo)= (100,100,100) (90,100,100) (75,100,100) (50,100,100)

Figure A1-c
Clp % of predicted value (400% to -200%)



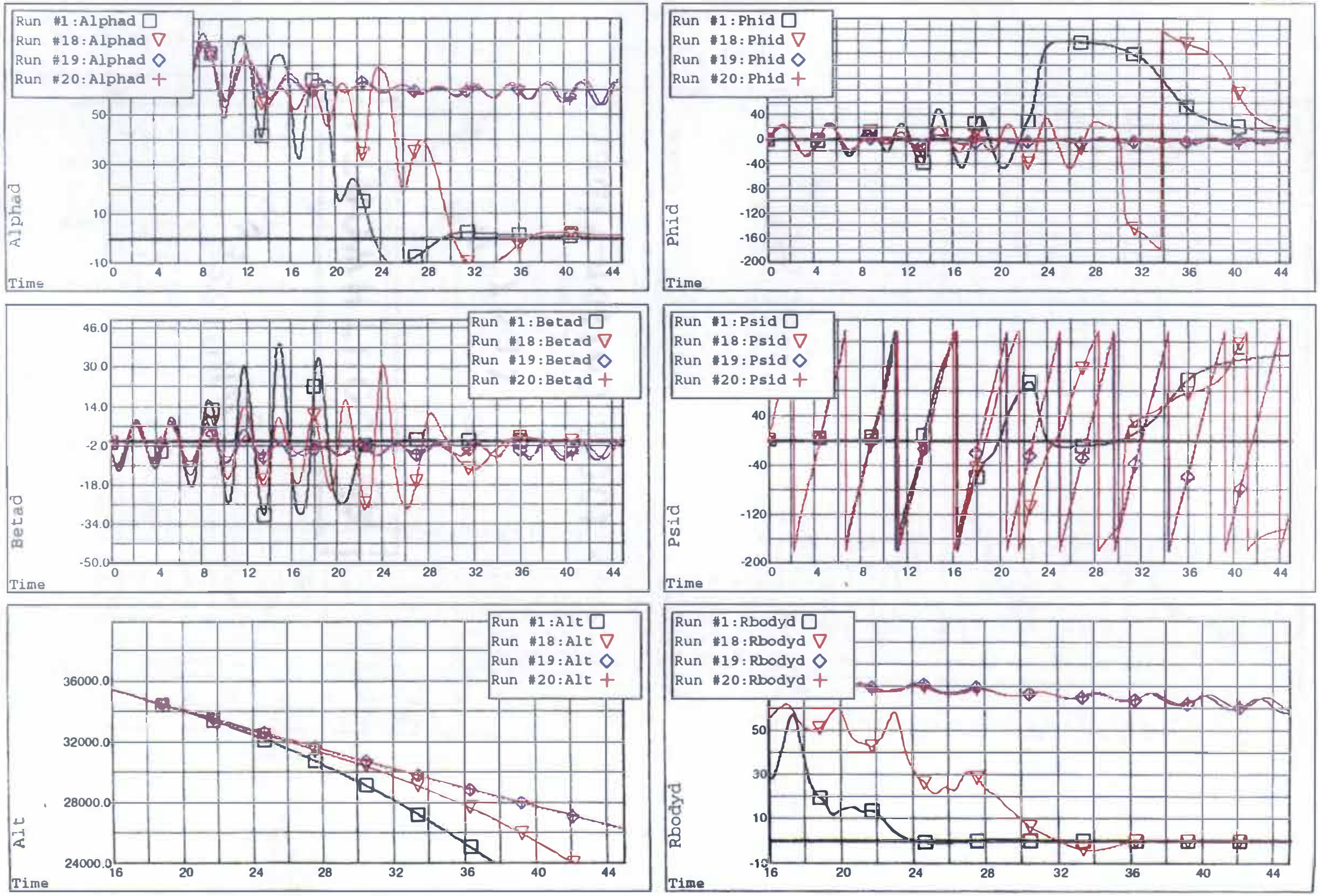
%(clp,clr,clo)= (100,100,100) (0,100,100) (-100,100,100) (-200,100,100)

Figure A1-d
Clp % of predicted value (400% to -200%)



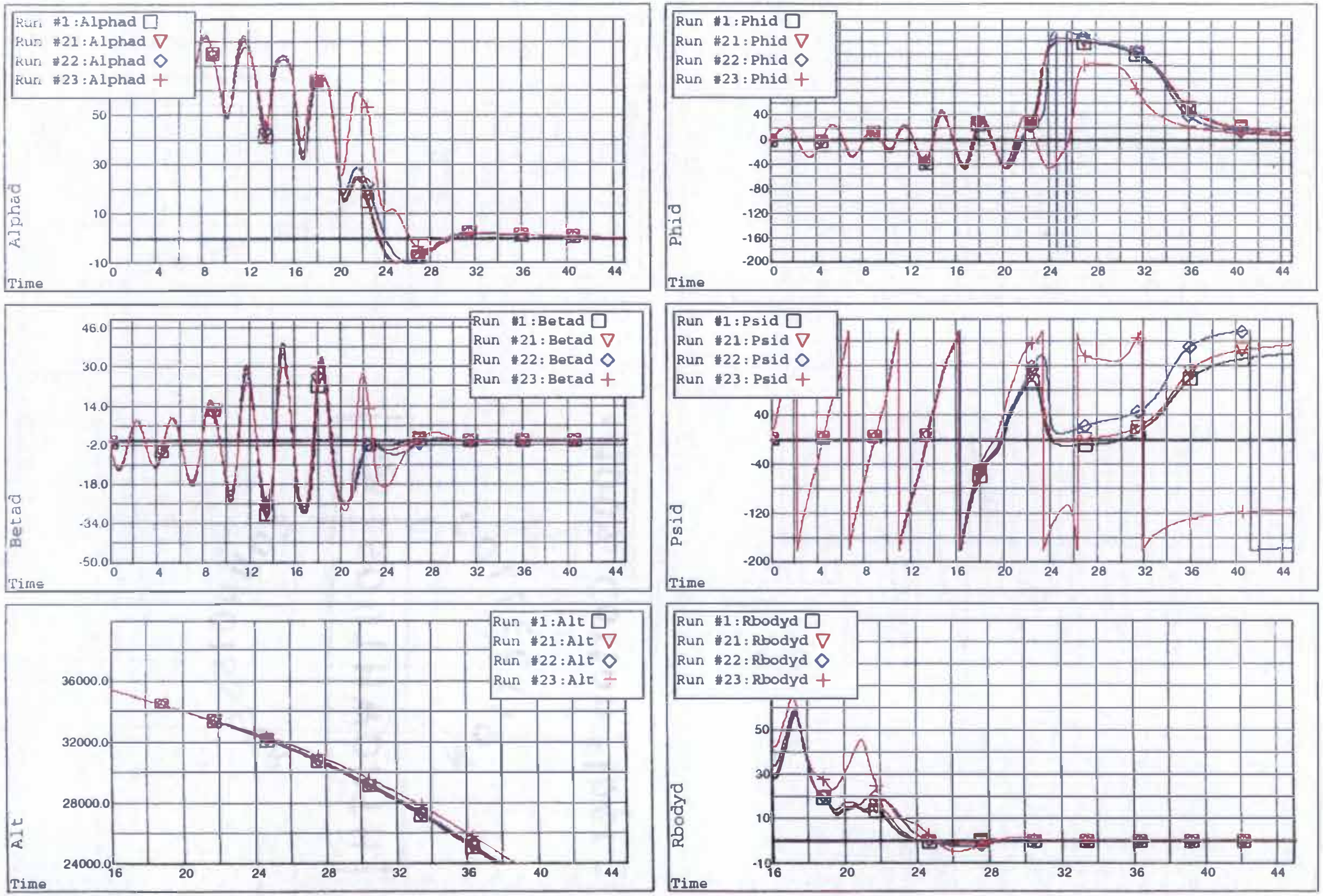
%(clp,clr,clo)=(100,100,100) (105,100,100) (110,100,100) (115,100,100)

Figure A1-e
Clp % of predicted value (400% to -200%)



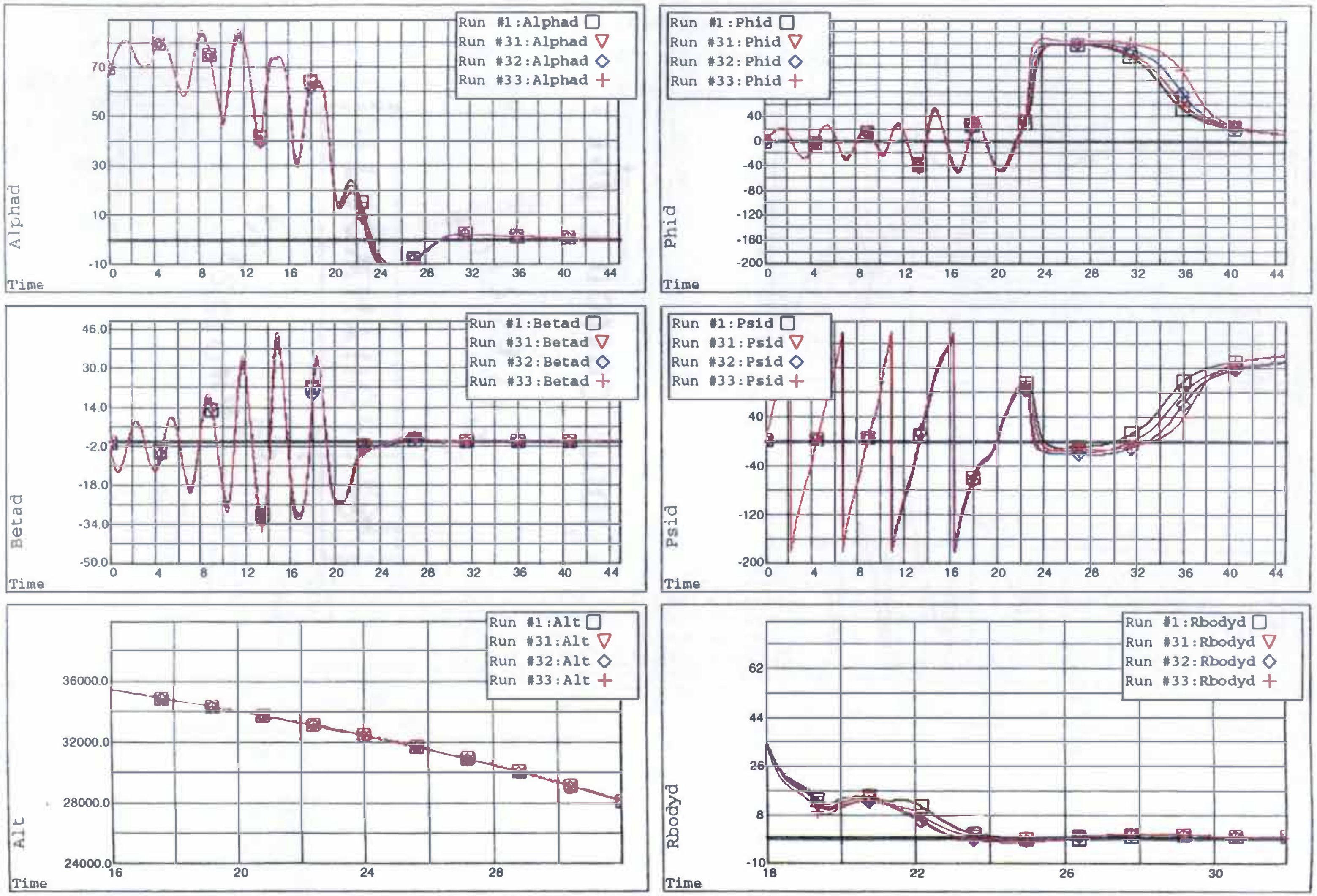
%(clp,clr,clo)= (100,100,100) (100,200,100) (100,300,100) (100,400,100)

Figure A2-a
Clr % of predicted value (400% to -200%)



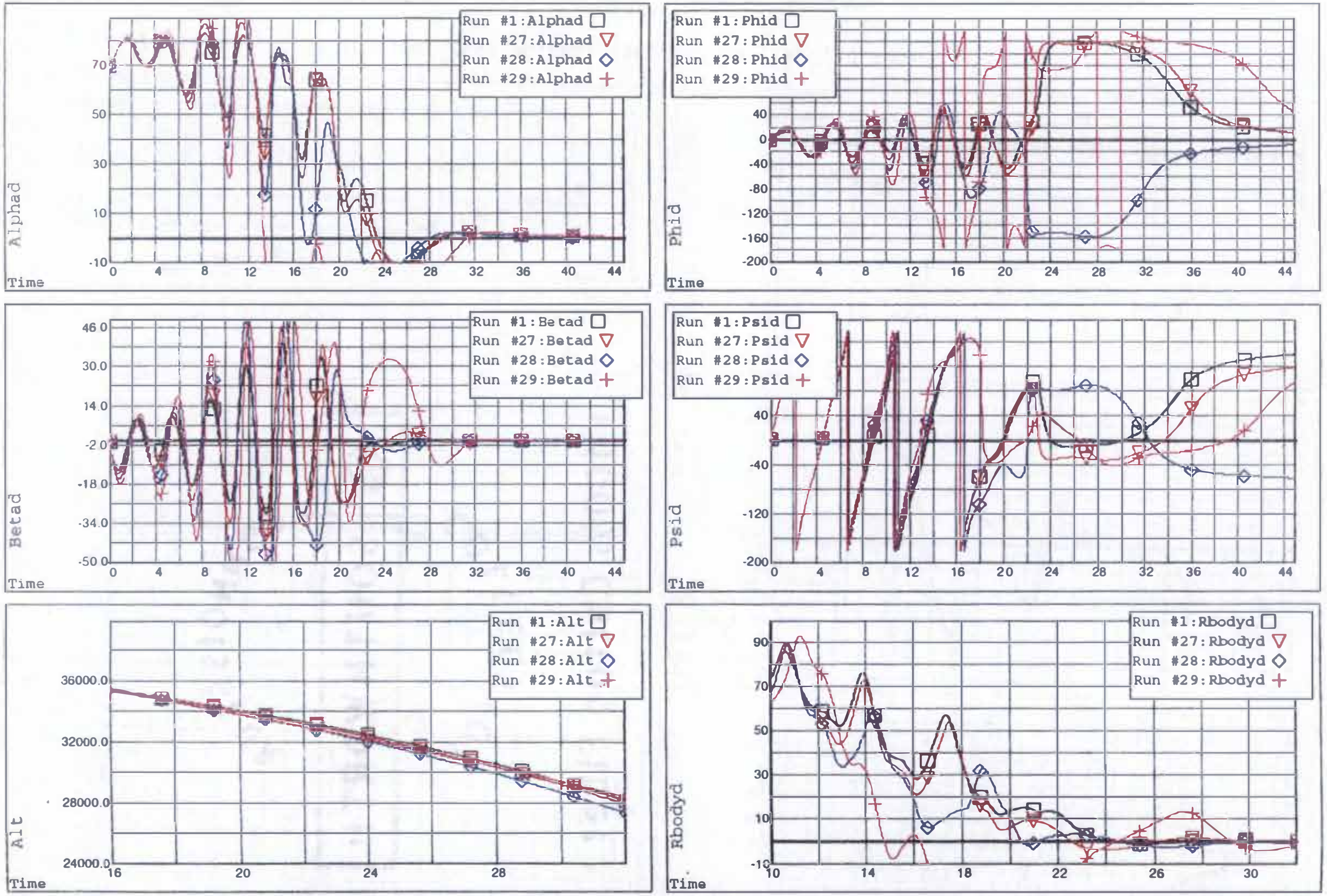
%(clp,clr,clo)= (100,100,100) (100,110,100) (100,125,100) (100,150,100)

Figure A2-b
Clr % of predicted value (400% to -200%)



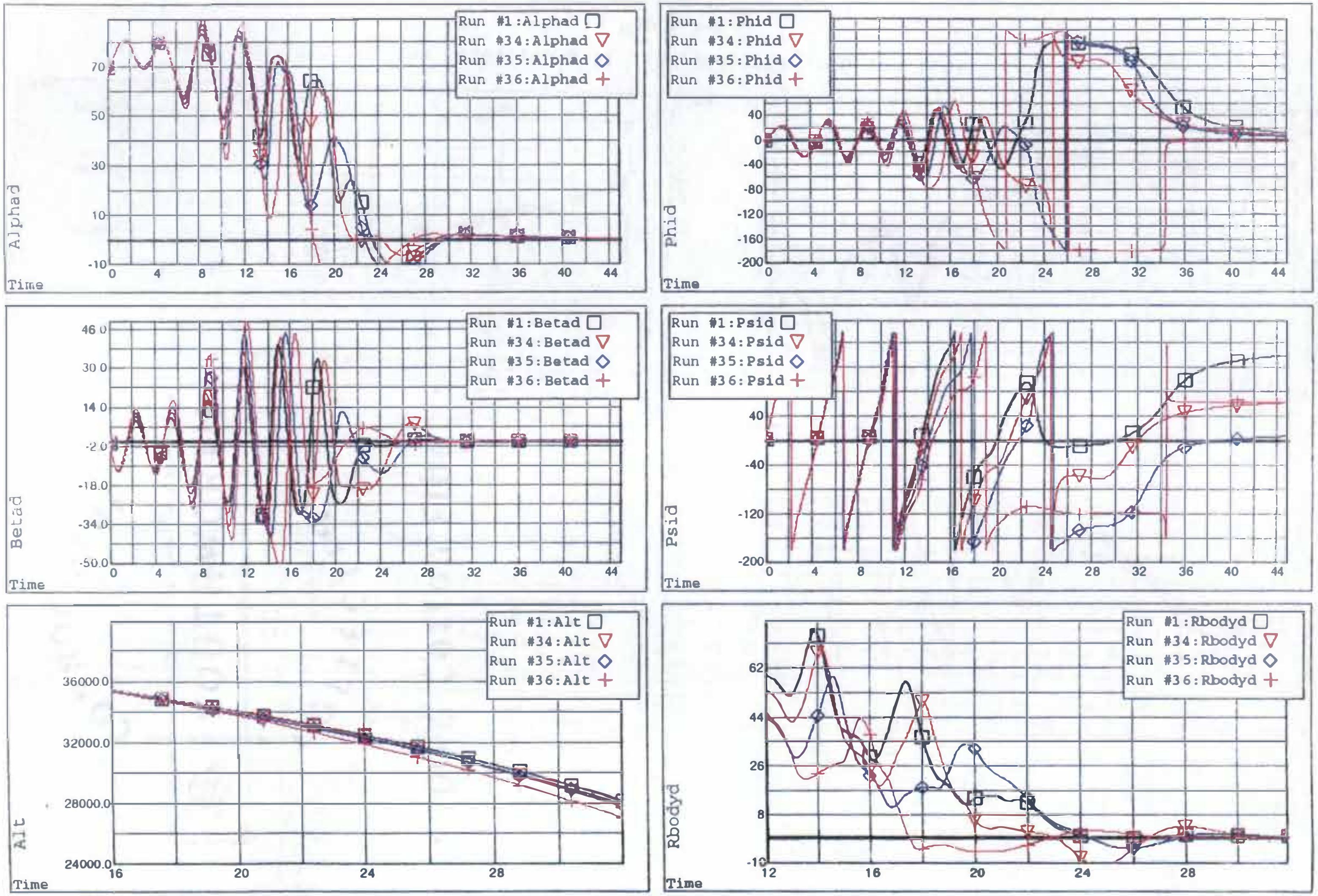
%(clp,clr,clo)=(100,100,100) (100,90,100) (100,75,100) (100,50,100)

Figure A2-c
Clr % of predicted value (400% to -200%)



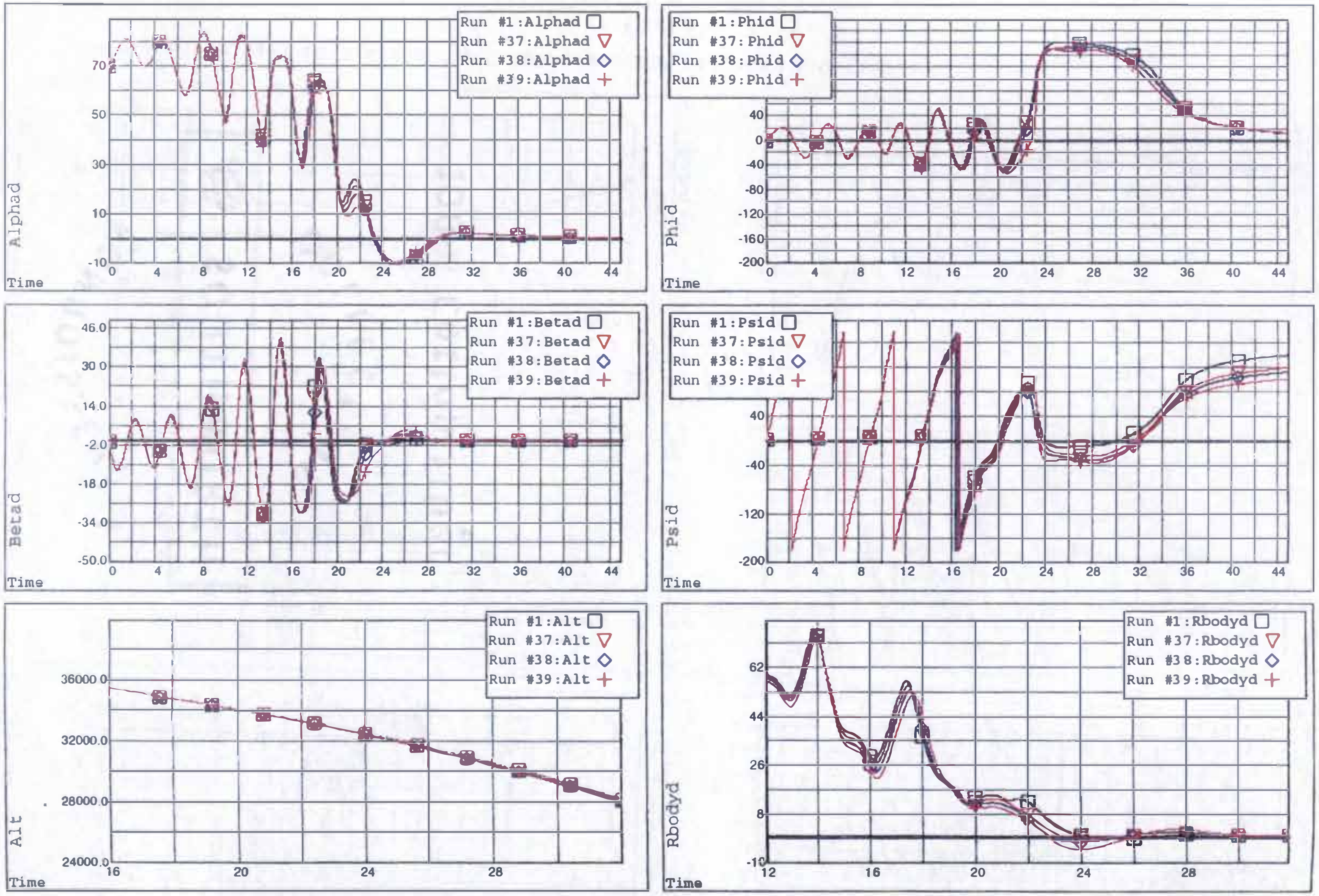
%(clp,clr,clo)=(100,100,100) (100,0,100) (100,-100,100) (100,-200,100)

Figure A2-d
Clr % of predicted value (400% to -200%)



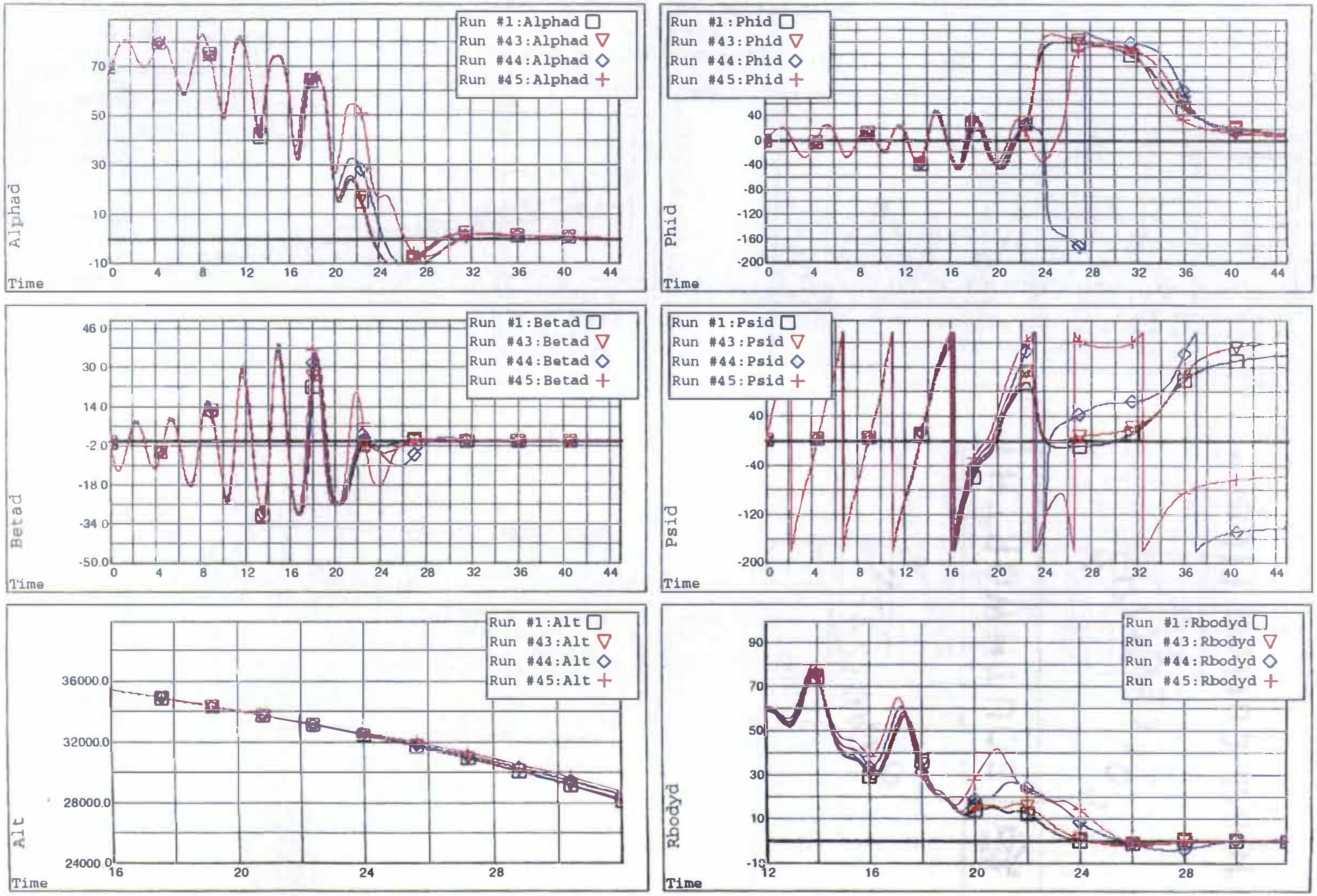
%(clp,clr,clo)=(100,100,100) (100,100,200) (100,100,300) (100,100,400)

Figure A3-a
ClΩ % of predicted value (400% to -200%)



%(clp,clr,clo)=(100,100,100) (100,100,110) (100,100,125) (100,100,150)

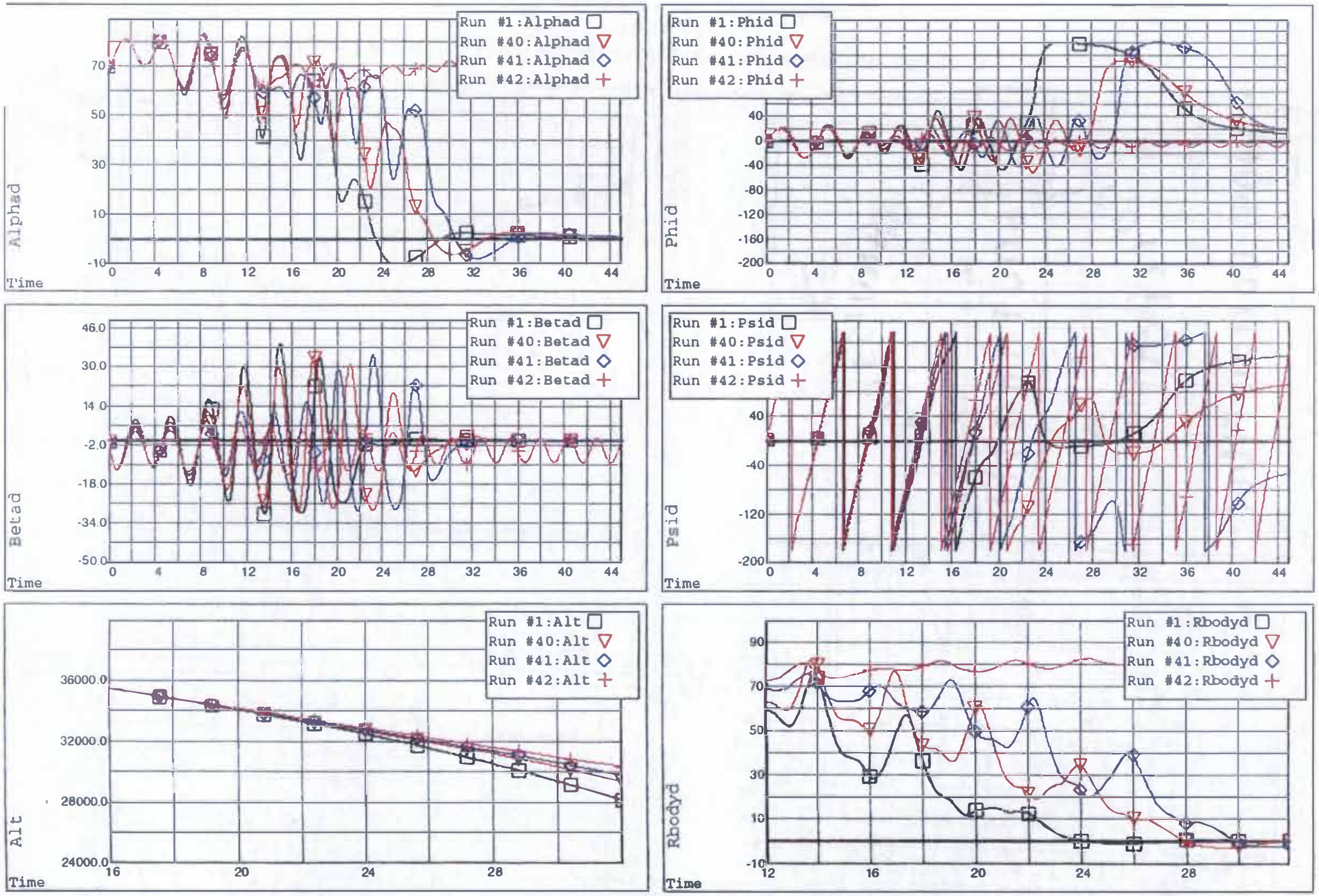
Figure A3-b
ClΩ % of predicted value (400% to -200%)



%(clp,clr,clo)=(100,100,100) (100,100,90) (100,100,75) (100,100,50)

Figure A3-c

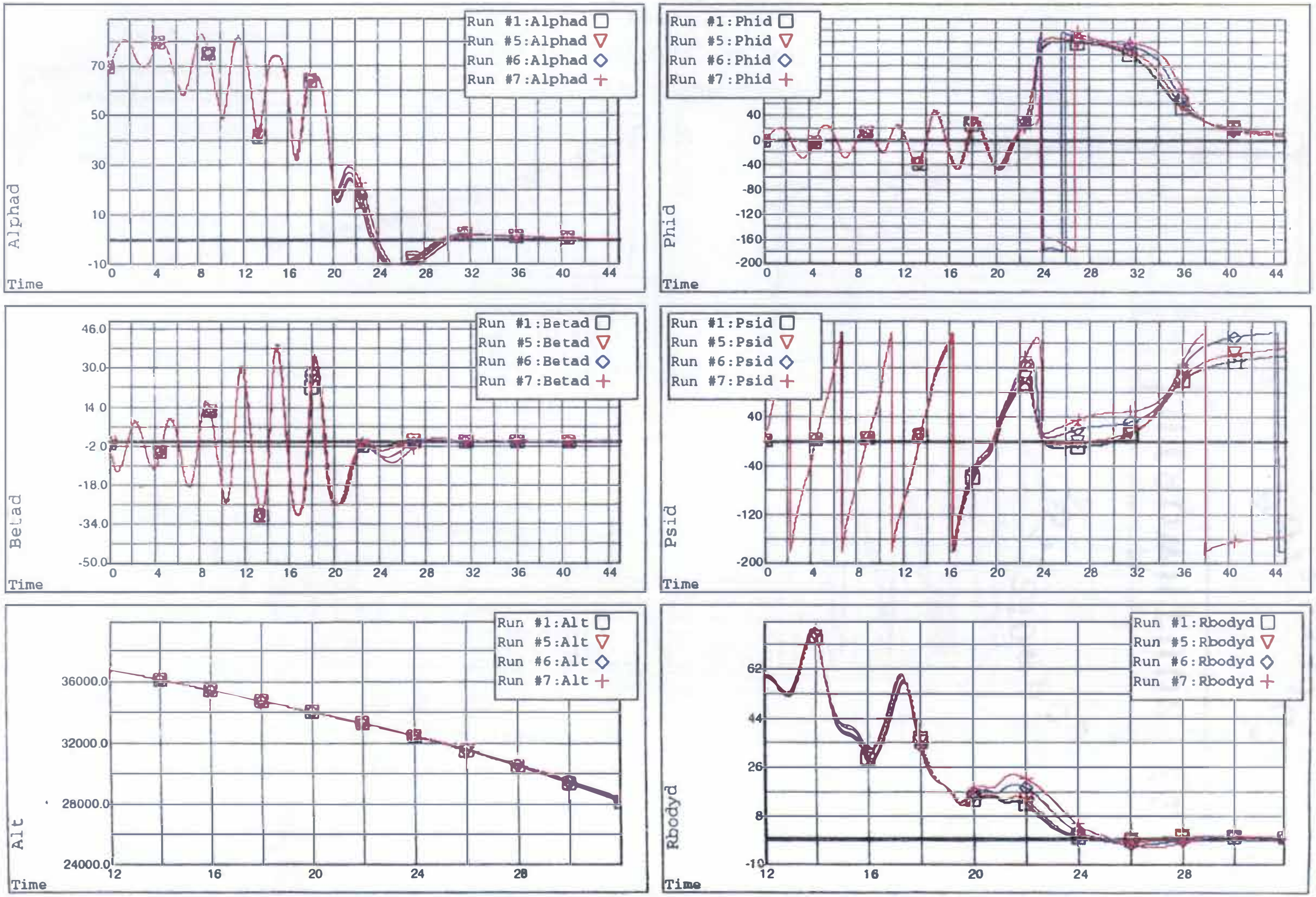
ClΩ % of predicted value (400% to -200%)



%(clp,clr,clo)=(100,100,100) (100,100,0) (100,100,-100) (100,100,-200)

Figure A3-d

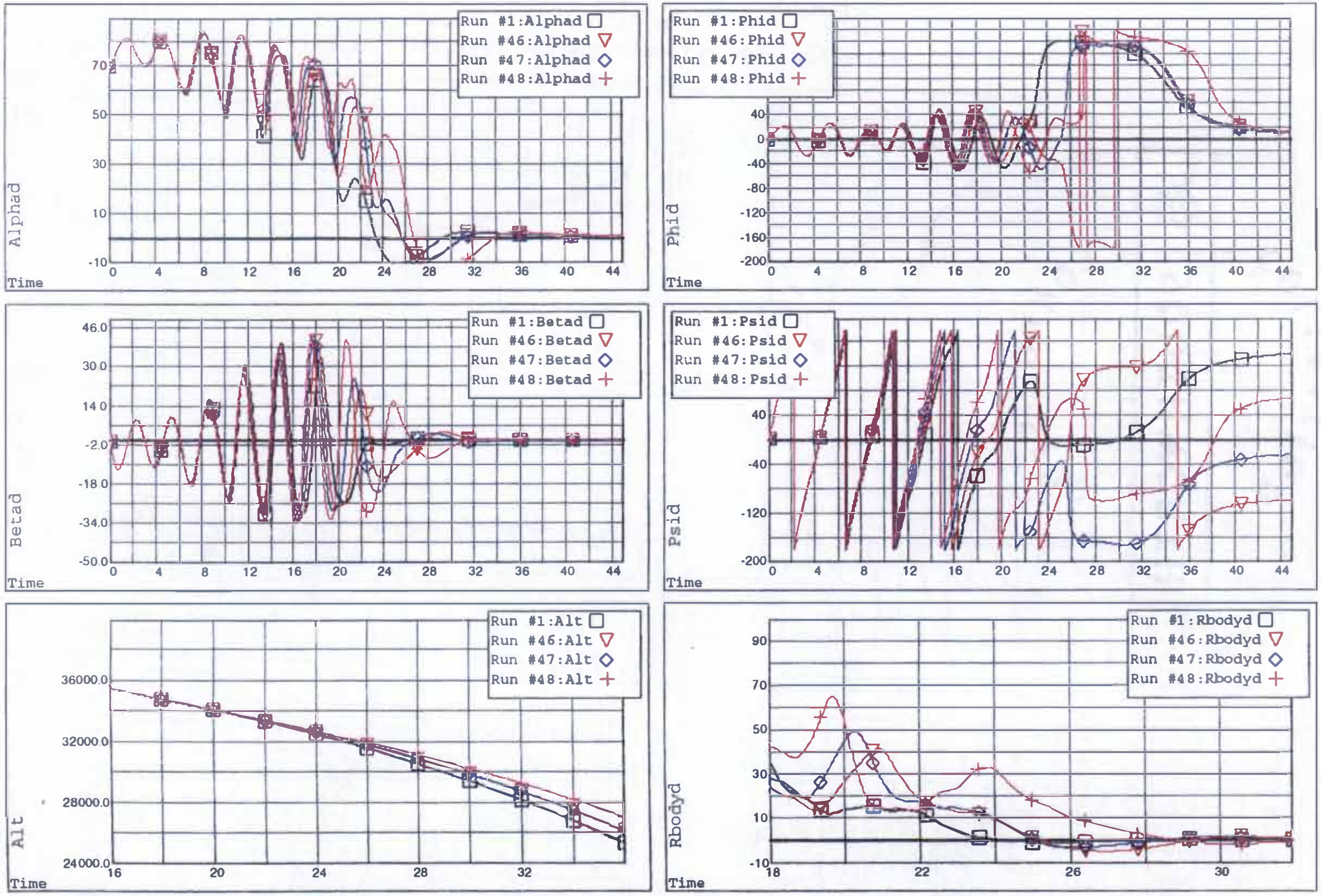
ClΩ % of predicted value (400% to -200%)



%(clp,clr,clo)=(100,100,100) (100,100,95) (100,100,85) (100,100,80)

Figure A3-e

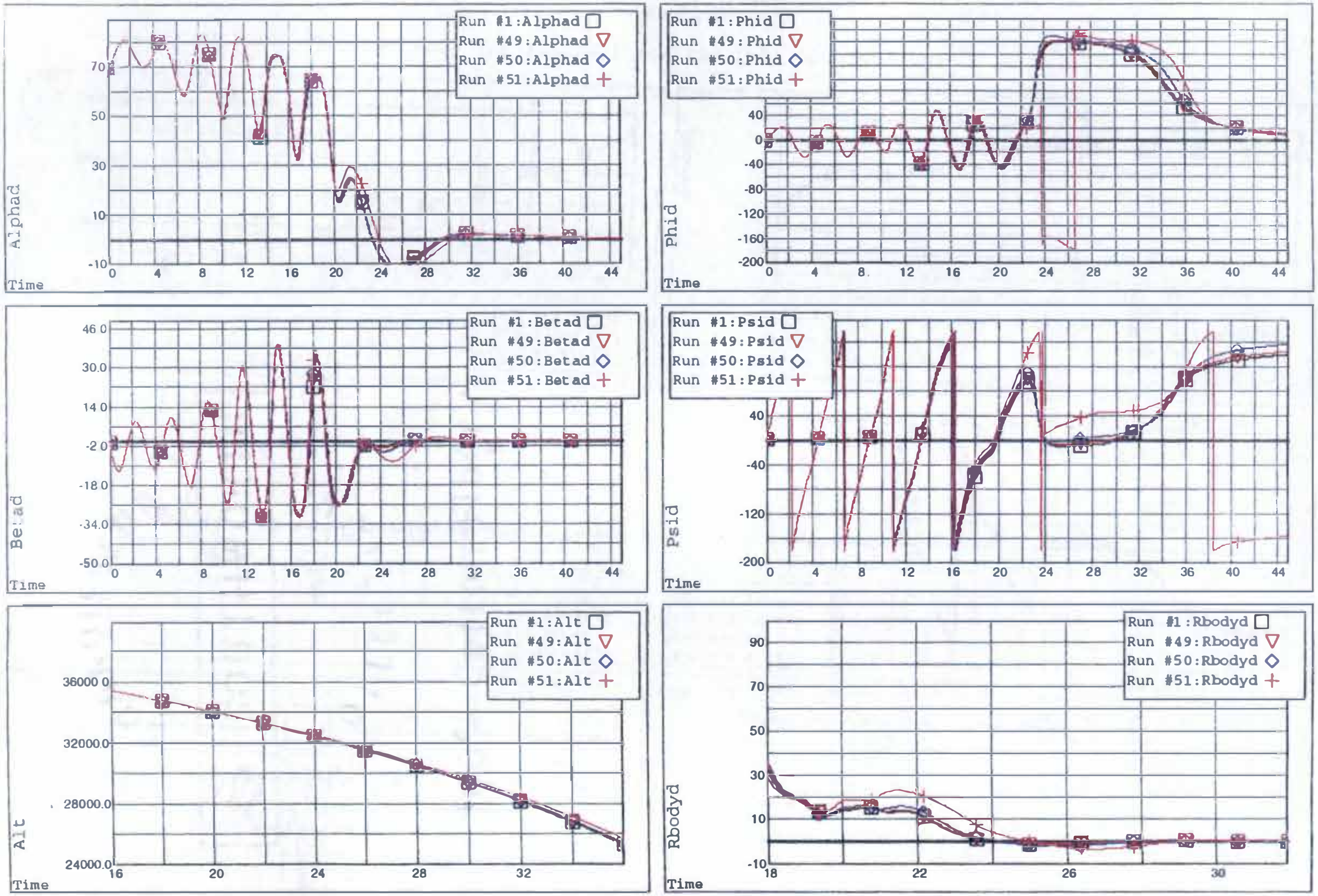
ClΩ % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (200,100,100) (300,100,100) (400,100,100)

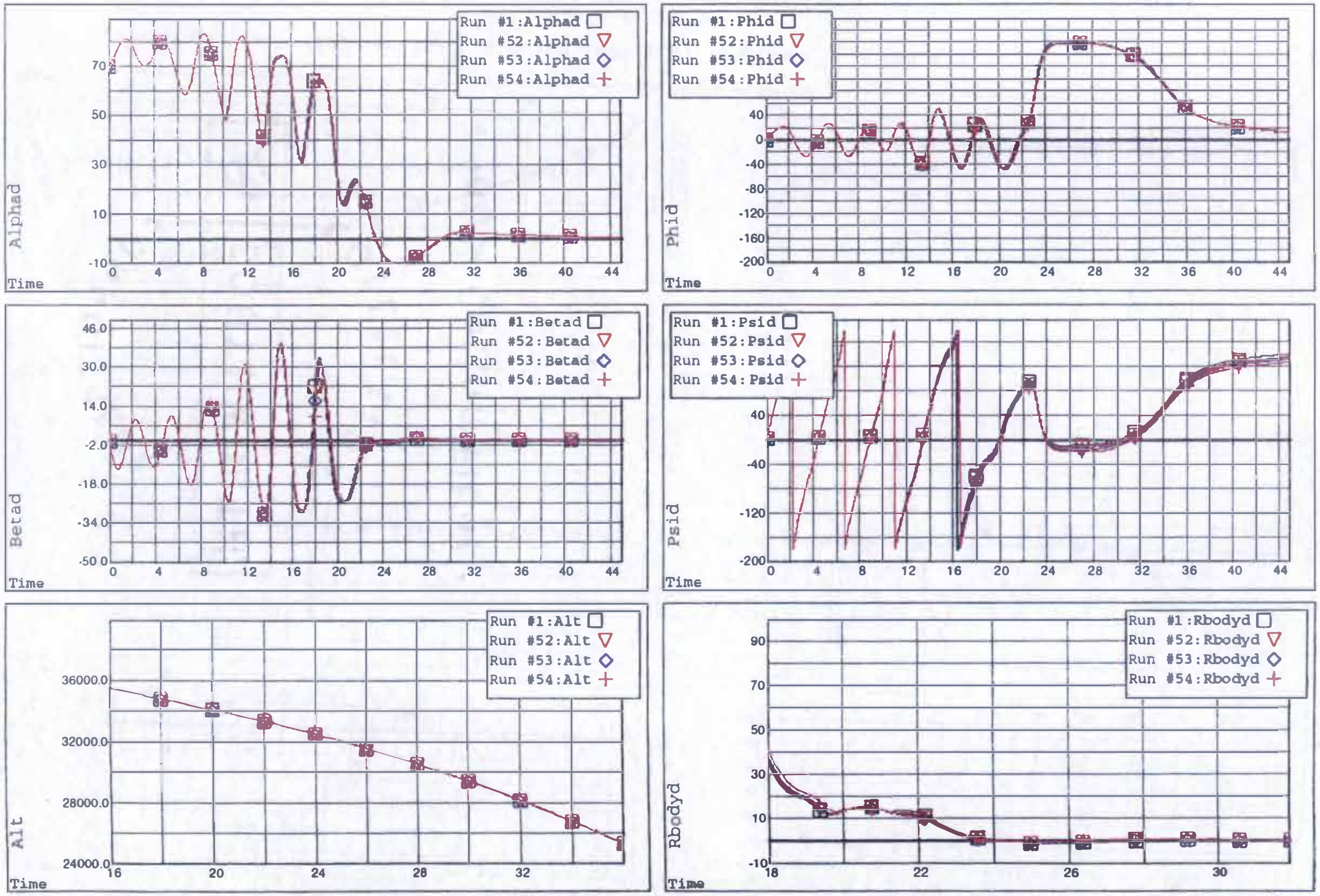
Figure A4-a

Cnp % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (110,100,100) (125,100,100) (150,100,100)

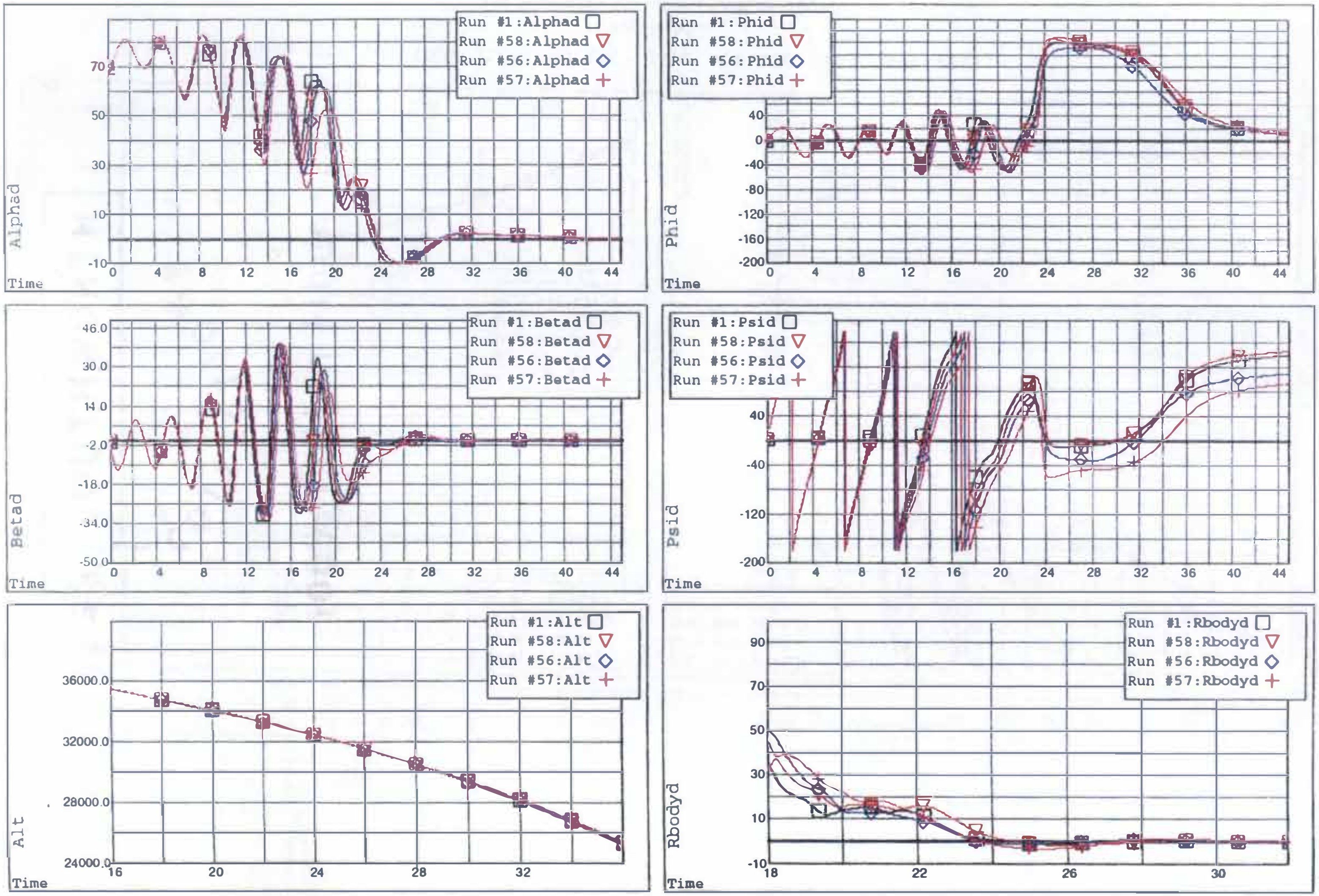
Figure A4-b
Cnp % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (90,100,100) (75,100,100) (50,100,100)

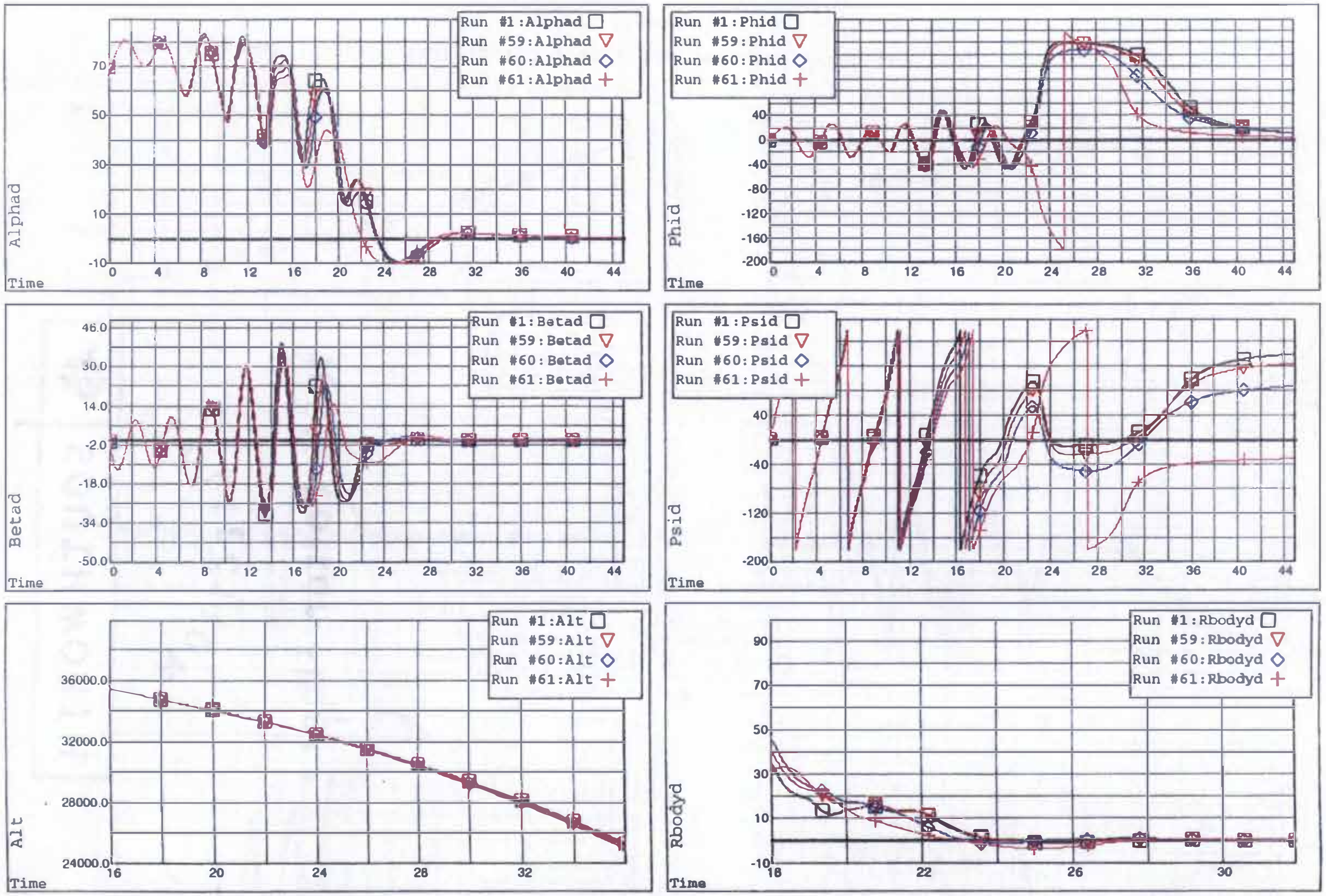
Figure A4-c

Cnp % of predicted value (400% to -200%)



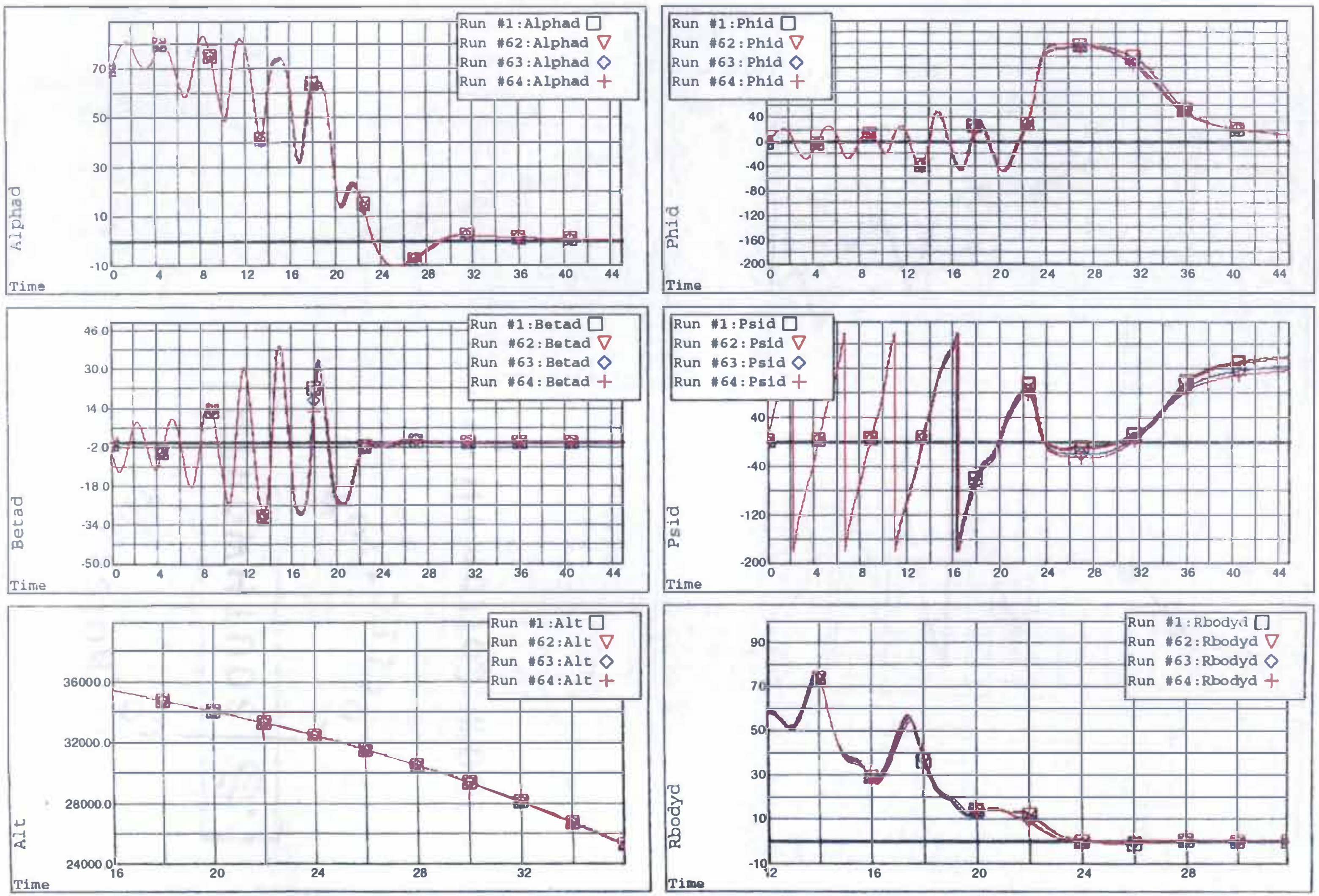
%(cnp,cnr,cno)=(100,100,100) (0,100,100) (-100,100,100) (-200,100,100)

Figure A4-d
Cnp % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,200,100) (100,300,100) (100,400,100)

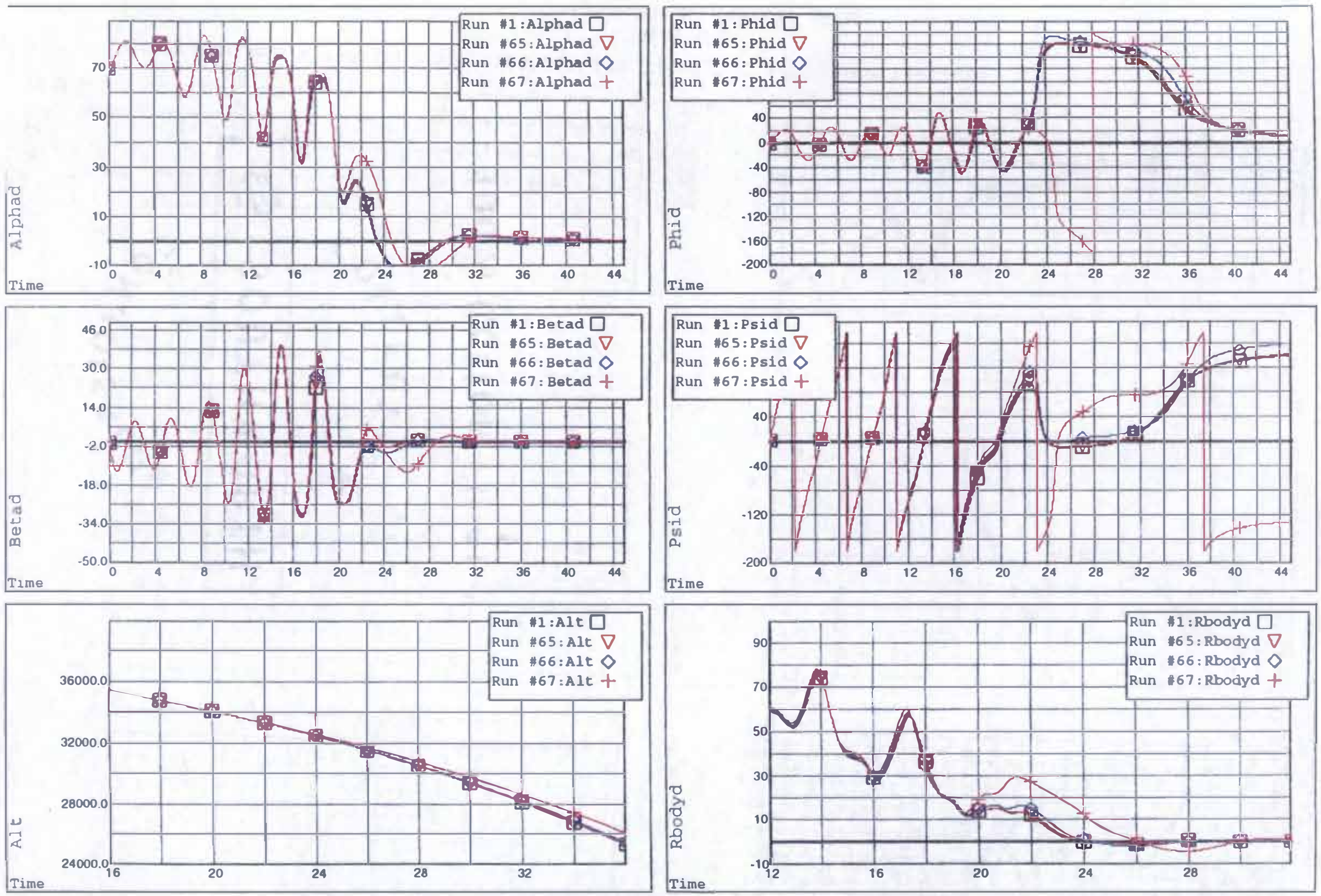
Figure A5-a
Cnr % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,110,100) (100,125,100) (100,150,100)

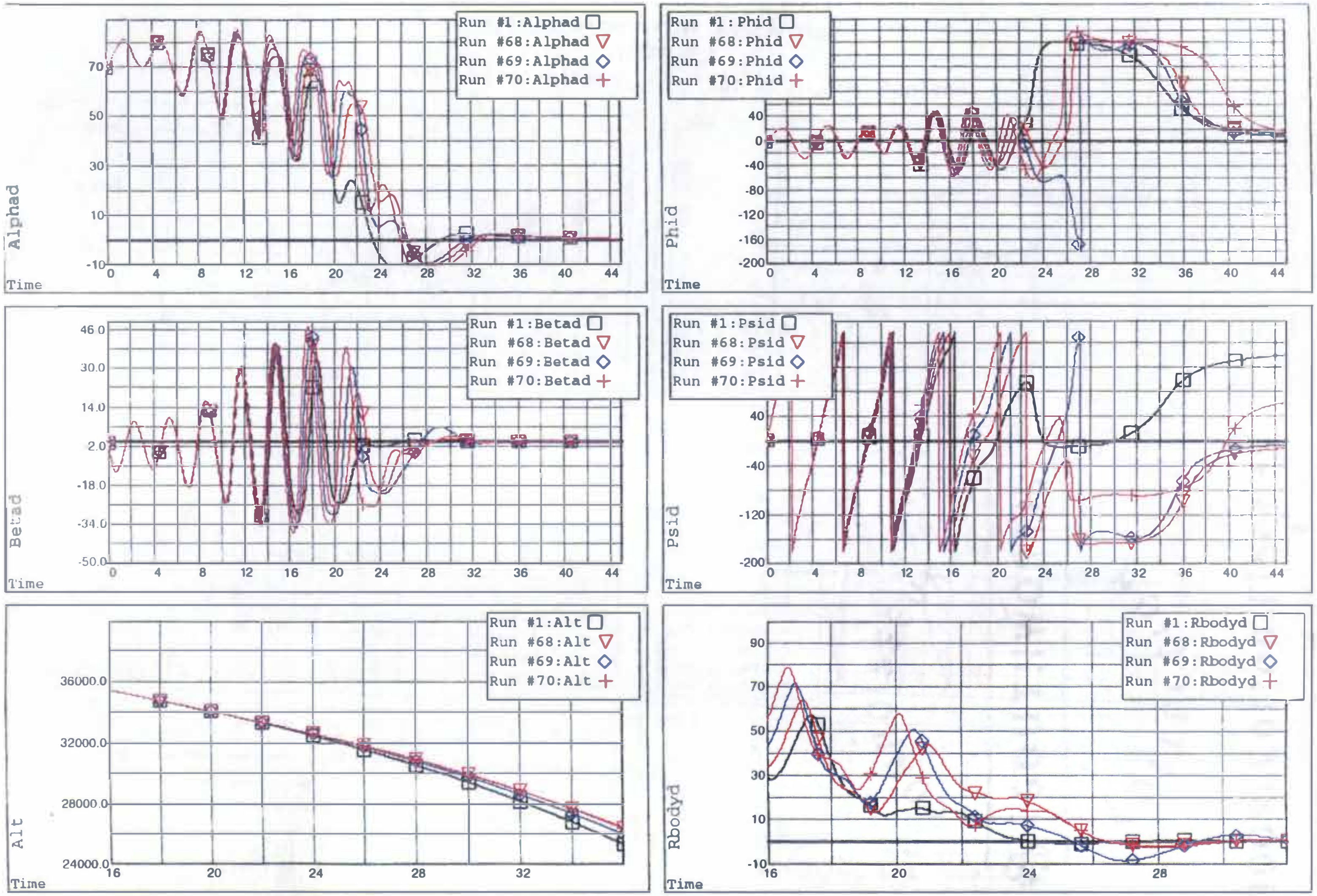
Figure A5-b

Cnr % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,90,100) (100,75,100) (100,50,100)

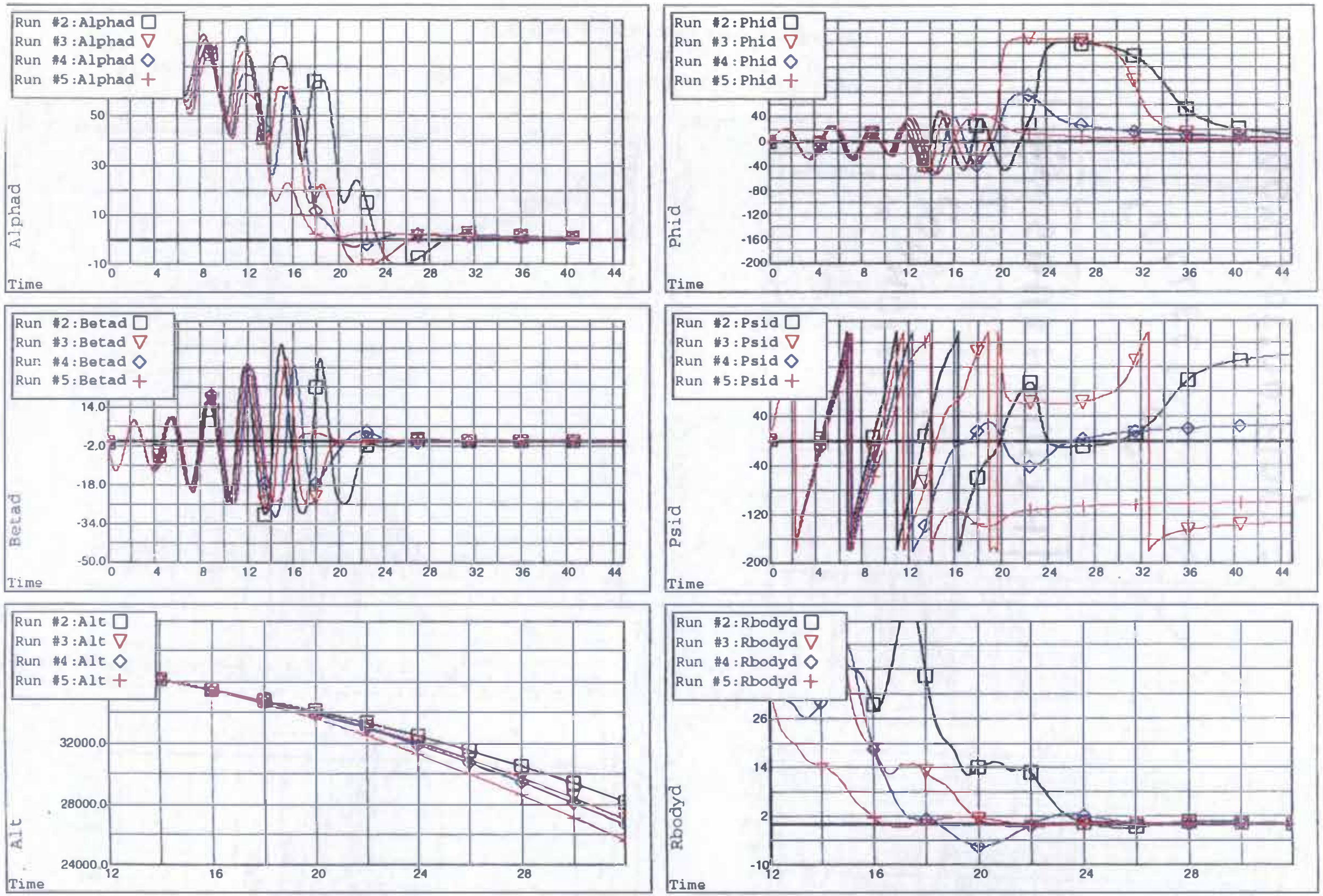
Figure A5-c
Cnr % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,0,100) (100,-100,100) (100,-200,100)

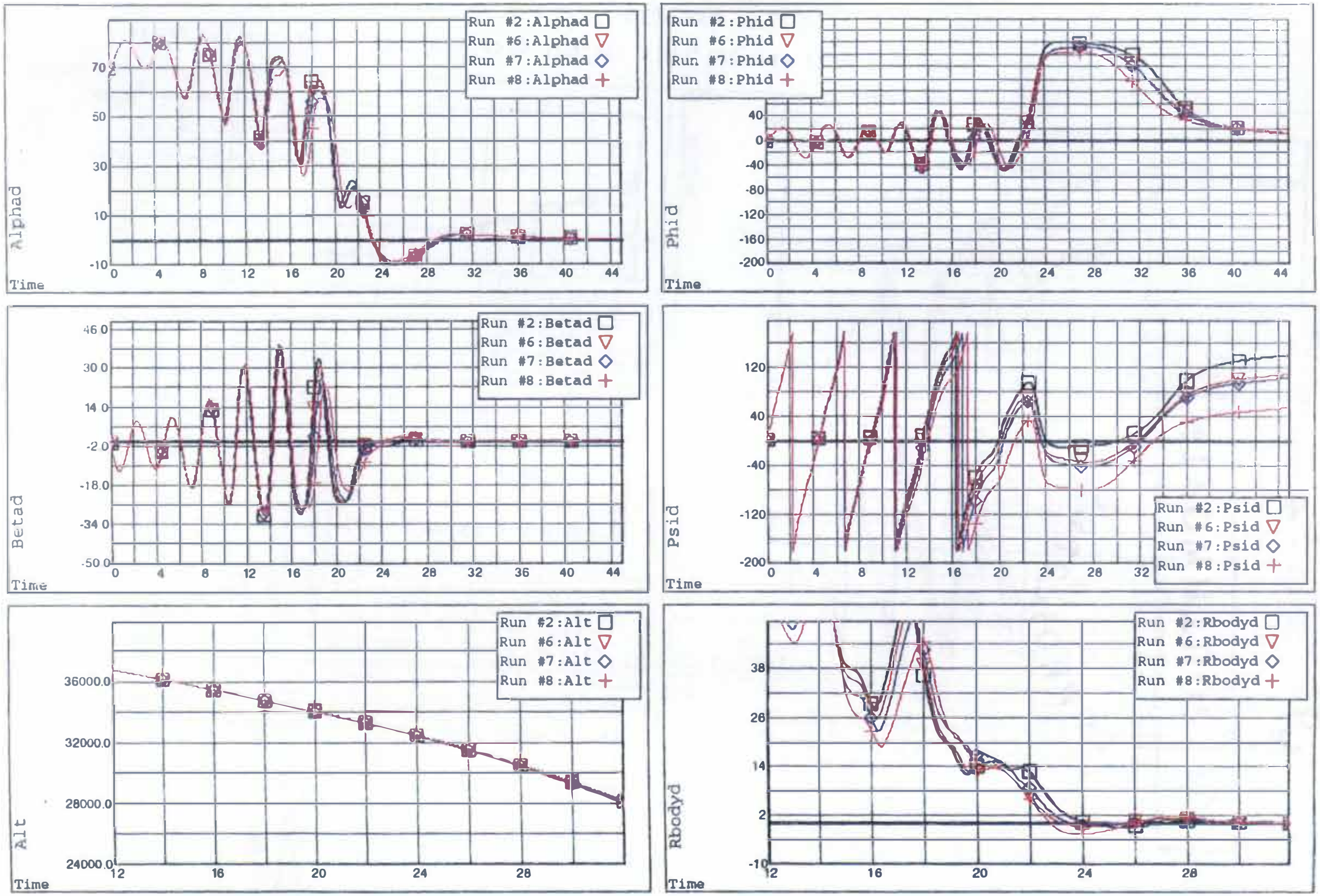
Figure A5-d

Cnr % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,100,200) (100,100,300) (100,100,400)

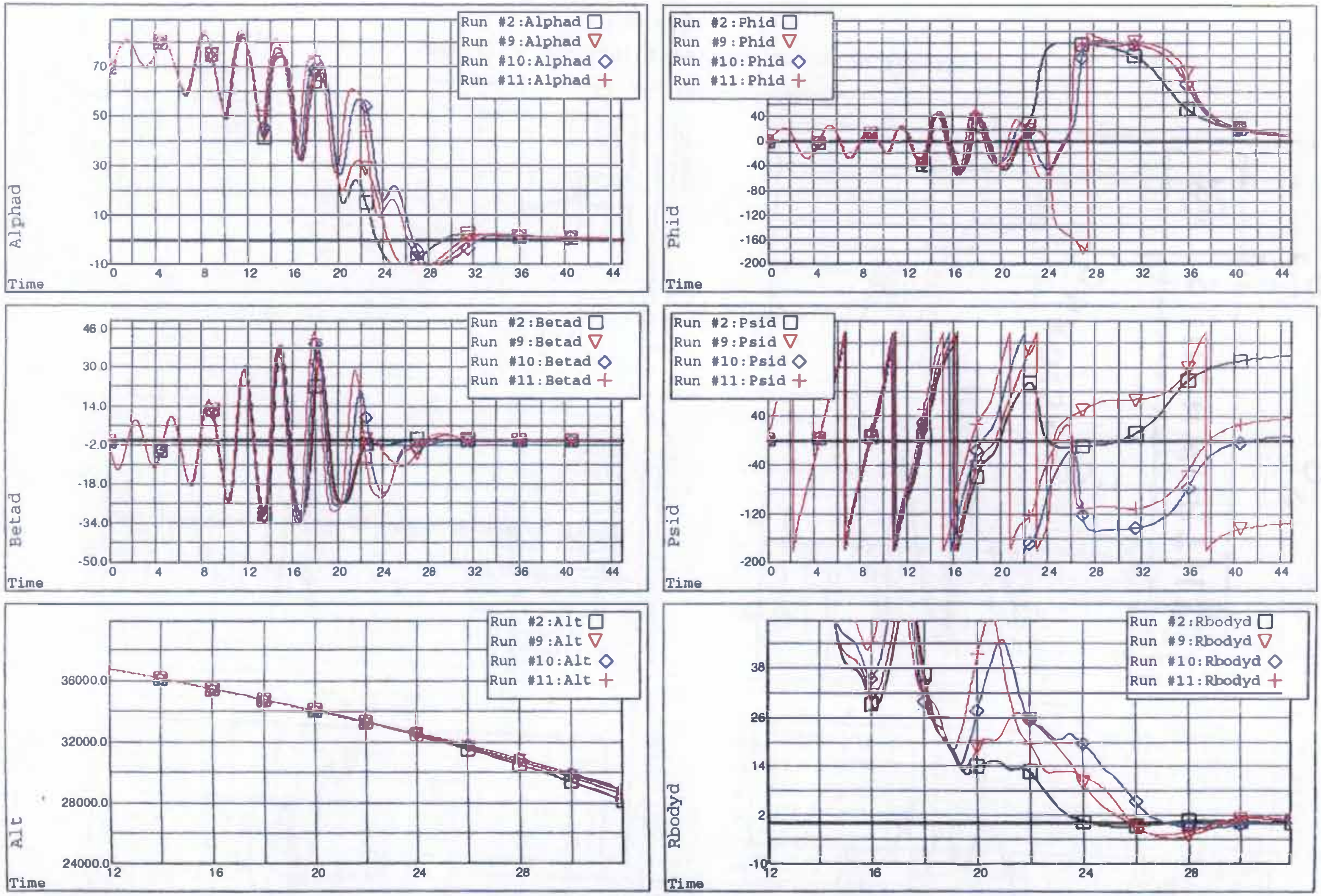
Figure A6-a
CnΩ % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,100,110) (100,100,125) (100,100,150)

Figure A6-b

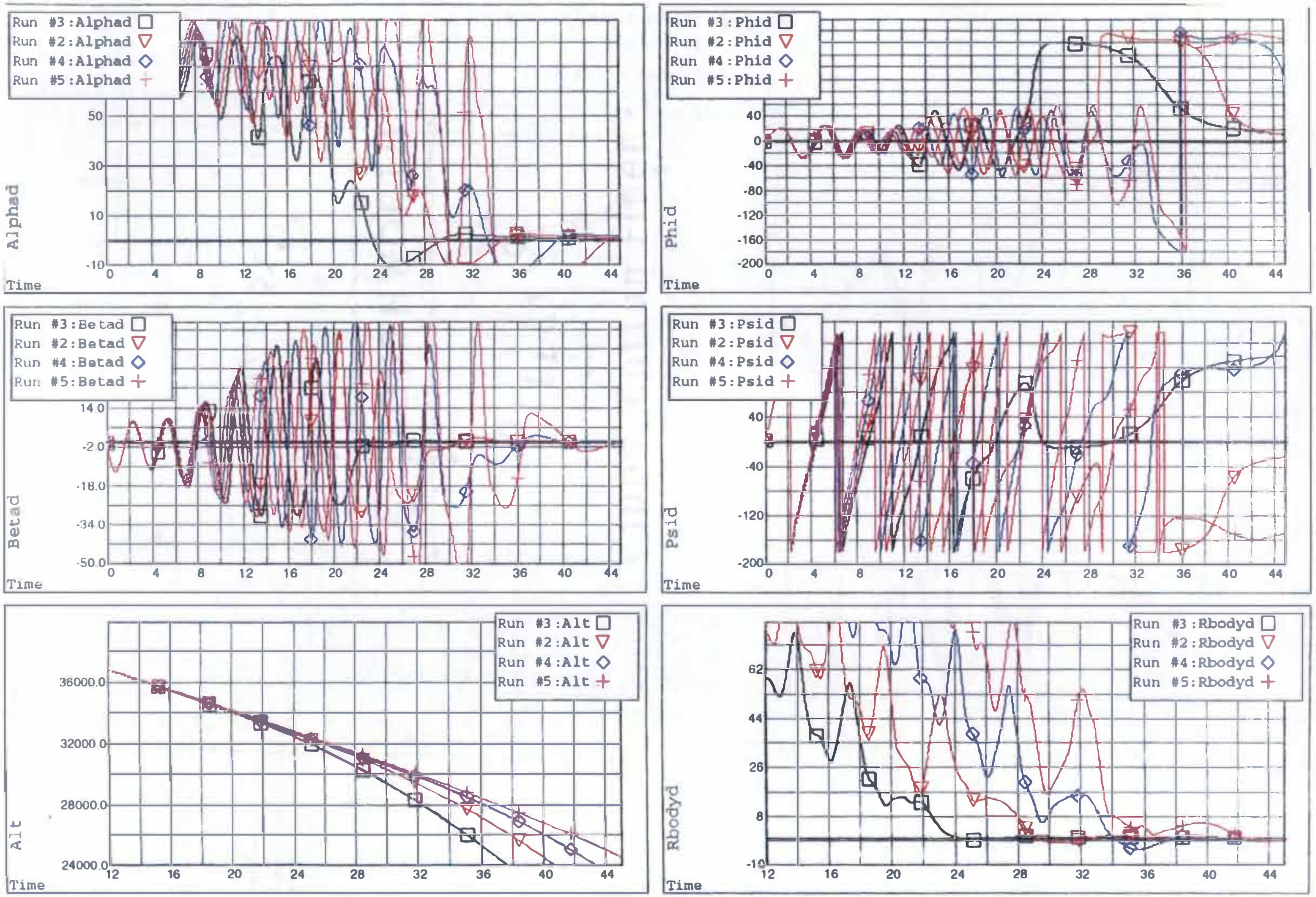
CnΩ % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,100,90) (100,100,75) (100,100,50)

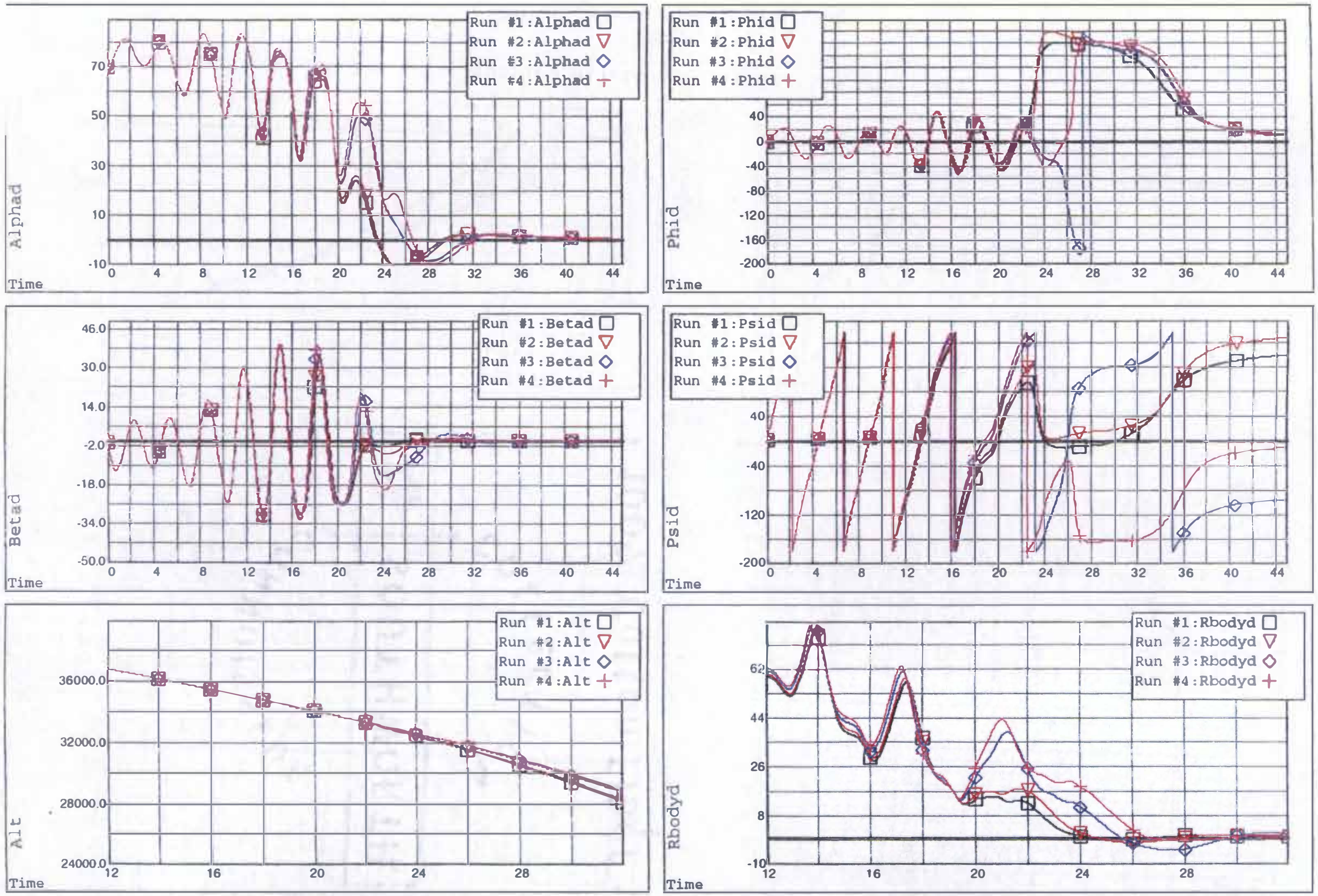
Figure A6-c

CnO % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,100,0) (100,100,-100) (100,100,-200)

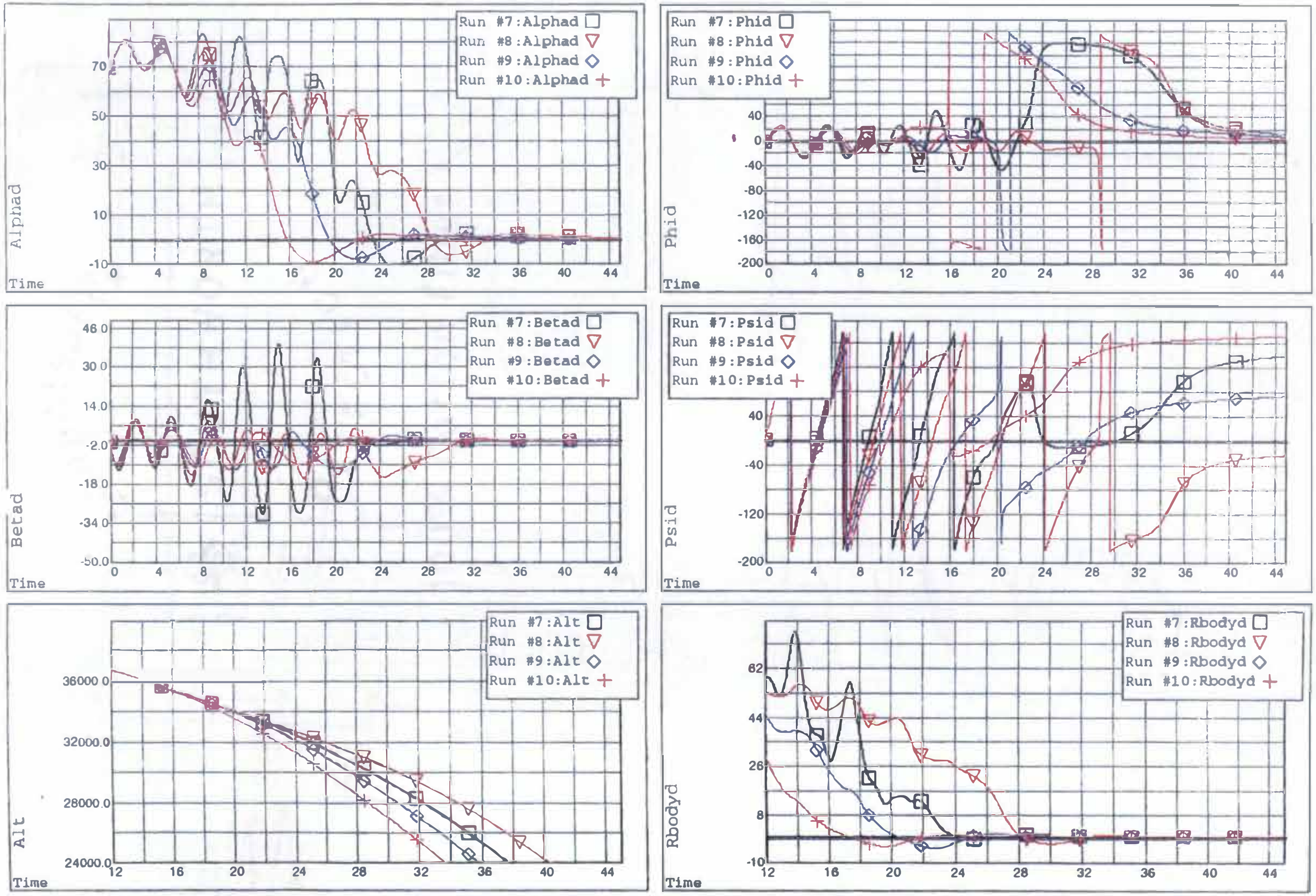
Figure A6-d
CnΩ % of predicted value (400% to -200%)



%(cnp,cnr,cno)=(100,100,100) (100,100,95) (100,100,85) (100,100,80)

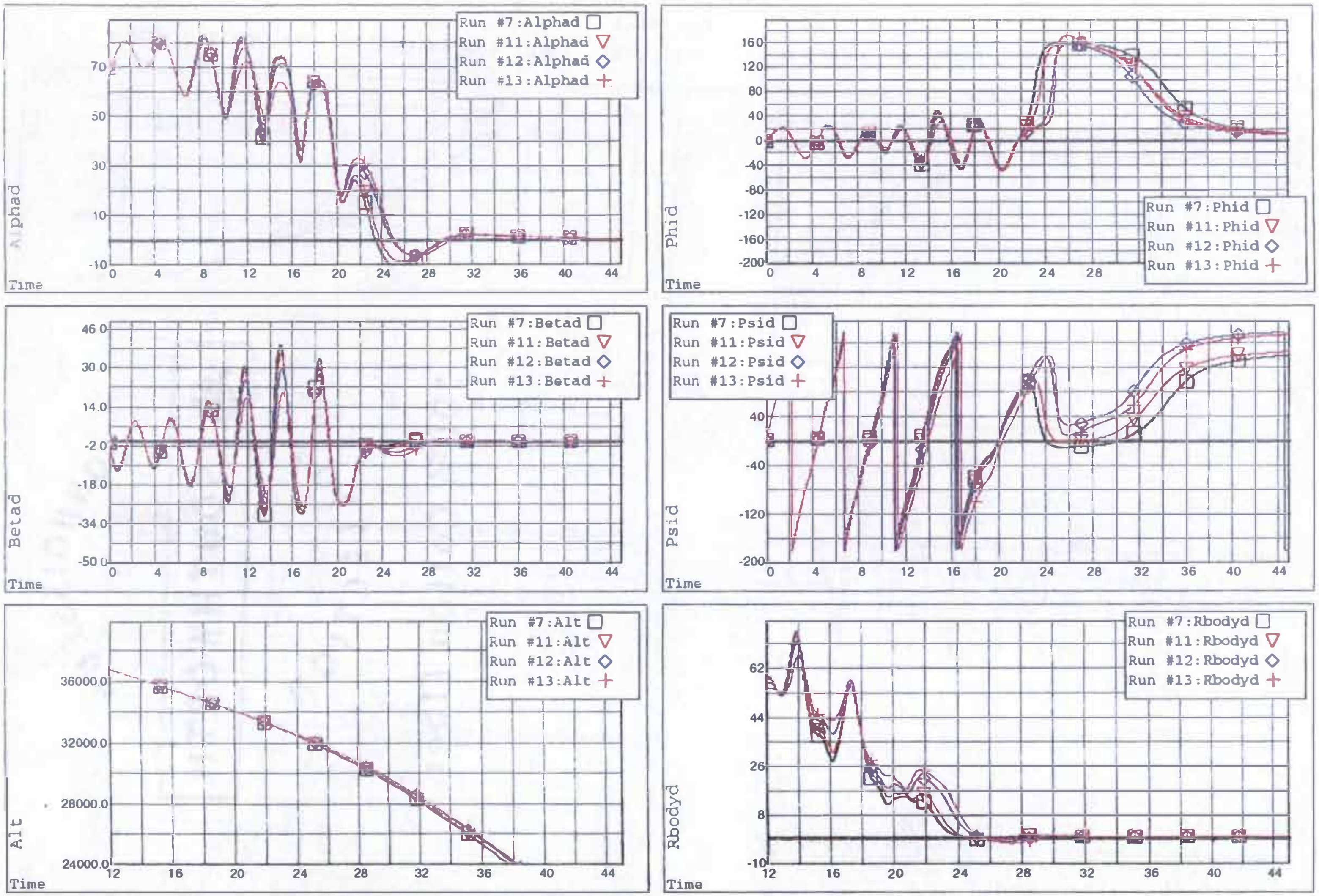
Figure A6-e

CnΩ % of predicted value (400% to -200%)



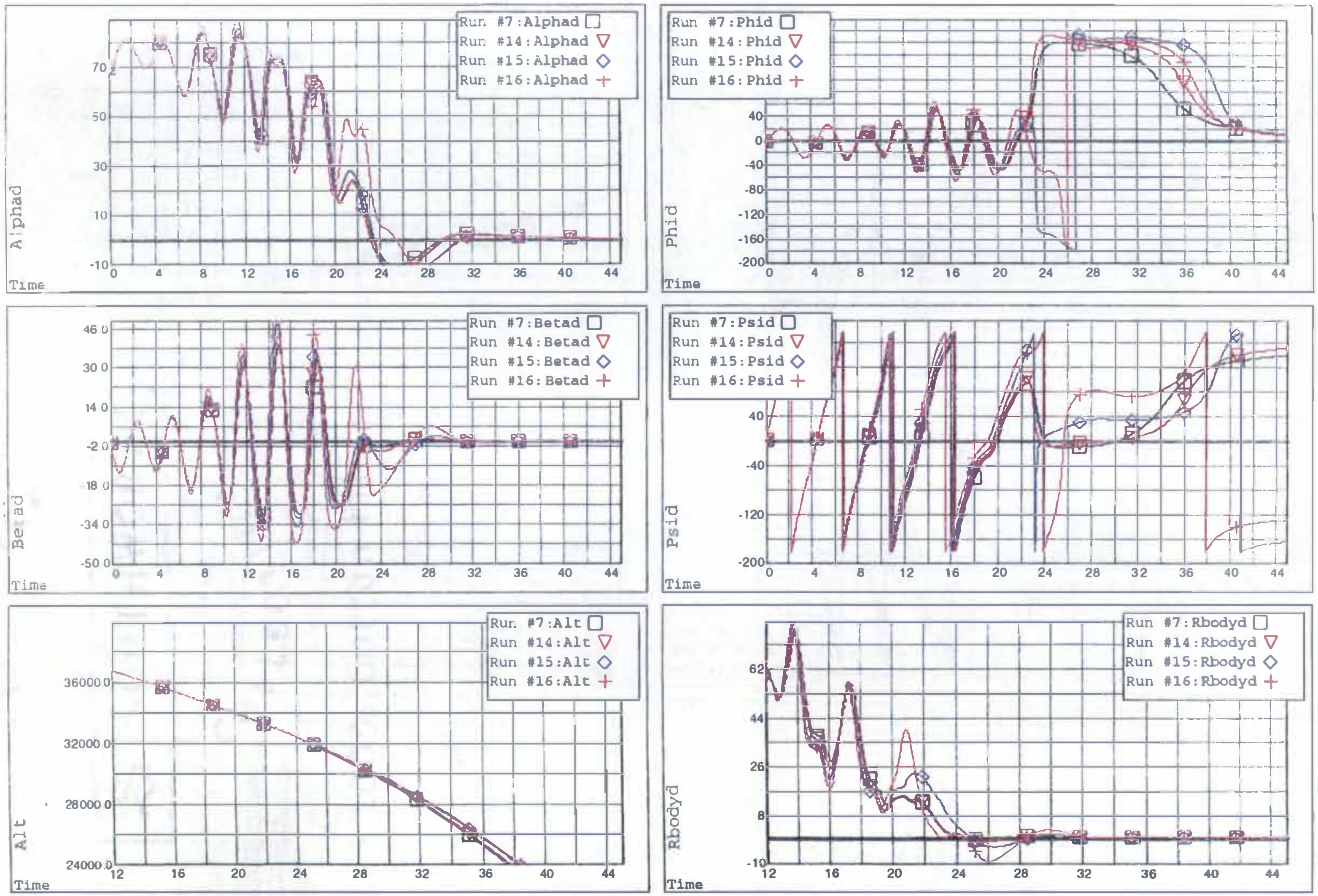
%(clp,clr,clo,cnp,cnr,cno)=(100) (200) (300) (400)

Figure A7-a
all % of predicted value (400% to -200%)



%(clp,clr,clo,cnp,cnr,cno)=(100) (110) (125) (150)

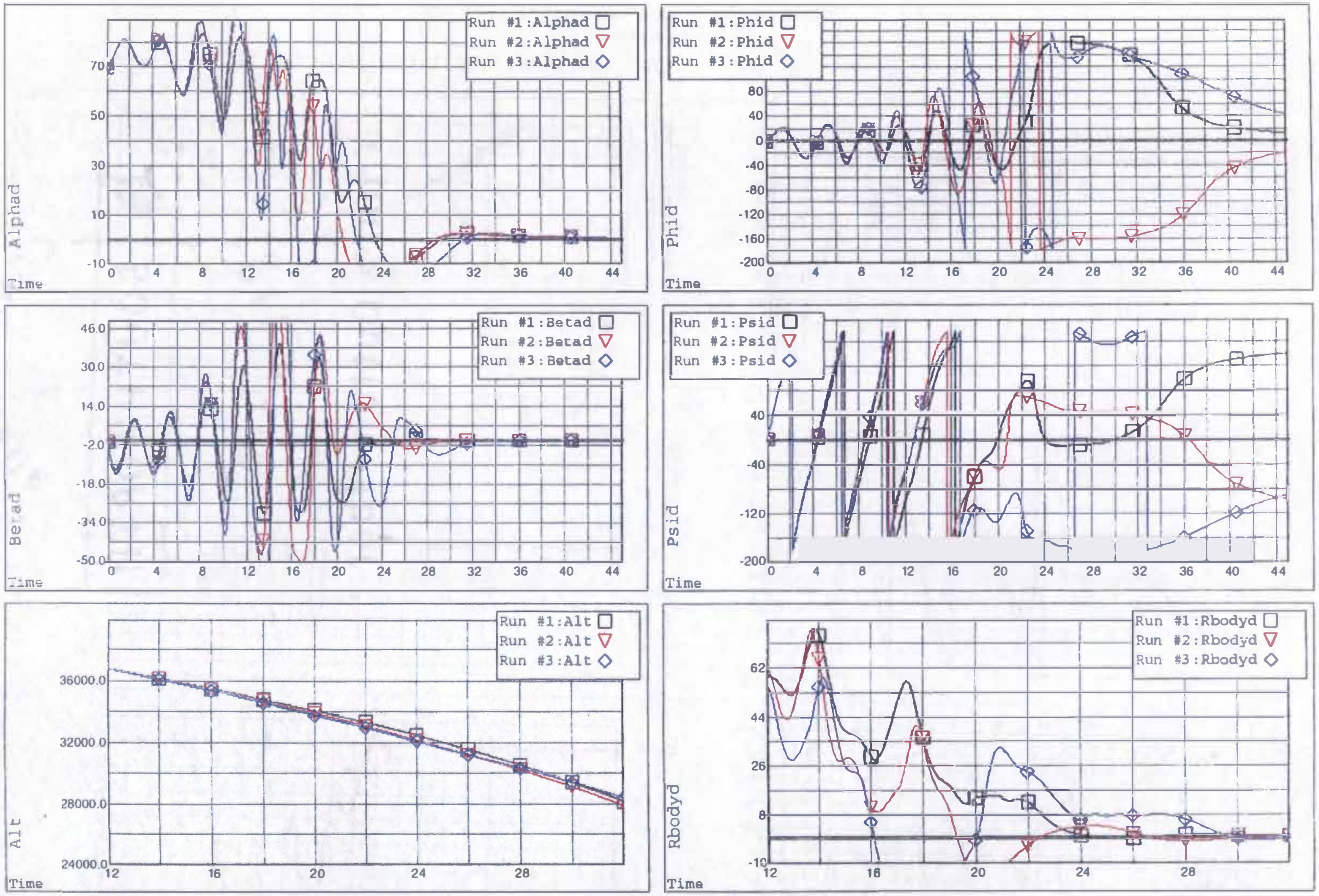
Figure A7-b
all % of predicted value (400% to -200%)



%(clp,clr,clo,cnp,cnr,cno)=(100) (90) (75) (50)

Figure A7-c

all % of predicted value (400% to -200%)



%(clp,clr,clo,cnp,cnr,cno)= (100) (25) (0)

Figure A7-d
all % of predicted value (400% to -200%)

VITA

Susan Jane DeGuzman was born in Newton, NJ on May 23, 1974. She was raised in Blairstown, NJ and attended Blairstown Elementary School and North Warren Middle School. She graduated from Pope John XXIII High School in 1992. She also received her private pilot's license in 1992. From there, she went to Rutgers University, New Brunswick NJ and received a B.S. in Mechanical/Aerospace Engineering in 1996.

Susan was hired by Naval Air Systems Command (NAVAIR) in 1996 to work as a Flight Dynamics engineer on the F/A-18E/F aircraft during it's development. During this time she received several achievement awards from RADM Dyer, CAPT Godwin, and Boeing for her engineering efforts on the F/A-18E/F program. In this office she became the lead engineer for several Naval aircraft including the T-45, AV-8B, EA-6B, and several unmanned aircraft programs. As a NAVAIR engineer Susan was sent to the Naval Test Pilot School in 1999 where she logged over 120 flight hours in various aircraft including: F/A-18, F-16, T-38, T-2, T-45, EA-6B, P3, CASA 101, H-60, H-6, King Air, Lear Jet, Boeing 707, and float planes. As a graduate of this school she completed a rigorous program of planning and writing complete flight test plans and reports of test results, including a full evaluation of an aircraft with the Spanish Air Force. As a NAVAIR employee she was also sent to the Naval Safety Center to work as an aircraft mishap investigator in 1998, where she performed detailed investigations of various Naval aircraft mishaps and analyzed aircraft components, flight and maintenance procedures, and design guidelines. Susan is currently working as an Airworthiness Officer at NAVAIR, and is married with one child and expecting her second immediately after graduation.

VITA